Applied Ergonomics 65 (2017) 316–325

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Review article

More than the Useful Field: Considering peripheral vision in driving

Benjamin Wolfe [a, b, *, 1], Jonathan Dobres [a, 2], Ruth Rosenholtz [b, c, 3], Bryan Reimer [a, 4]

[a] AgeLab, Massachusetts Institute of Technology, United States
[b] CSAIL, Massachusetts Institute of Technology, United States
[c] Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, United States

A R T I C L E I N F O

Article history:
Received 19 July 2016
Received in revised form
29 June 2017
Accepted 19 July 2017

Keywords:
UFOV
Useful field of view
Peripheral vision
Visual attention

A B S T R A C T

Applied research on driving and basic vision research have held similar views on central, fovea-based vision as the core of visual perception. In applied work, the concept of the Useful Field, as determined by the Useful Field of View (UFOV) test, divides vision between a "useful" region towards the center of the visual field, and the rest of the visual field. While compelling, this dichotomization is at odds with findings in vision science which demonstrate the capabilities of peripheral vision. In this paper, we examine driving research from this new perspective, and argue for the need for an updated understanding of how drivers acquire information about their operating environment using peripheral vision. The concept of the Useful Field and the UFOV test are not discarded; instead we discuss their strengths, limitations, and future directions. We discuss key findings from vision science on peripheral vision, and a theory that provides insights into its capabilities and limitations. This more complete basic science understanding of peripheral vision informs appropriate use of the UFOV and the Useful Field in driving research going forward.

Contents

* Corresponding author. AgeLab, Massachusetts Institute of Technology, United States.
E-mail addresses: bwolfe@mit.edu (B. Wolfe), jdobres@mit.edu (J. Dobres), rruth@mit.edu (R. Rosenholtz), reimer@mit.edu (B. Reimer).
[1] 77 Massachusetts Ave, 32-D540, Cambridge, MA 02139.
[2] 77 Massachusetts Ave, E90-905, Cambridge, MA, 02139.
[3] 77 Massachusetts Ave, 32-D532, Cambridge, MA, 02139.
[4] 77 Massachusetts Ave, E90-9042, Cambridge, MA, 02139.

http://dx.doi.org/10.1016/j.apergo.2017.07.009

1. Introduction

An essential question in applied research is “what can the driver perceive and act on at a given point in time?” Efforts to understand the driver's limitations gave rise to the Useful Field of View (UFOV) test – a tool for probing what a driver, particularly an older driver, could attend to in a larger scene (Ball and Owsley, 1993). For clarity in this paper, when we talk of the UFOV, we are referring to the test, and when we refer to the Useful Field, we are discussing the measured region in space defined by performance on the UFOV test. The UFOV has proven to be a powerful assessment tool, as we discuss in the body of the paper. However, hand-in-hand with the use of the UFOV as a tool, some research using it has also adopted a simplified model of vision during driving, in which the Useful Field describes the only available visual input. This narrow concept of the Useful Field was summarized by Anderson and colleagues as “Any information that falls within the UFOV is processed whereas any information that falls outside of this region is not processed.” (2011). Under this conception of vision, it is only what is within a driver's Useful Field that truly matters, and the visual field beyond it – in the periphery – is unavailable or, perhaps, acknowledged as being useful for lane-keeping and little else. We will dispute this narrow conception of the Useful Field and consider peripheral vision more broadly in this paper from a basic vision science perspective.

In contrast to the size of the Useful Field (often assessed to be 15-20° radially from the fovea), the human binocular visual field affords a remarkably wide view of the world – in excess of 90° to the left and right, and more than 60° above and below (Traquair, 1927). The Useful Field, as assessed by the UFOV test, covers only a small portion of the entire visual field. Anatomically, however, *peripheral vision is the entirety of the visual field beyond the fovea* and, when we refer to peripheral vision in this paper, we are using this encompassing definition. There are profound differences between foveal and peripheral vision, as is immediately apparent from our own daily experiences. In large part, this is a function of the underlying anatomy; the fovea, the location of highest photoreceptor density in the retina, is disproportionally represented in visual cortex (Tootell et al., 1982), resulting in more detailed representations compared to the periphery. Given this weighting in the brain, the human visual system may seem to be built around our need to foveate objects in the world, and peripheral vision may appear only to exist to provide enough information to move the eyes to where they need to be pointed. The temptation, then, is to see the central visual field (the fovea plus parafovea, occupying about $\pm 4°$ of visual angle about the point of fixation), as “where the important vision happens”. The idea of the Useful Field expands this important region considerably, but falls far short of the full extent of the visual field, essentially ignoring the region beyond, at most, the central 15-20°. However, a deeper understanding of peripheral vision suggests that this Useful Field-centric account underestimates the utility of peripheral vision.

The driving literature has appreciated the importance of vision across the entire visual field in the context of maintaining situational awareness of the driving environment (Endsley, 1988; Smith and Hancock, 1995). Situational awareness requires integration of visual information from the entire visual field (Gugerty, 2011), although the theory thereof focuses on attending to individual objects in the environment (Endsley, 1988). We will define *attention* (see (Carrasco, 2011) for a review) for the purposes of this paper as the process of bringing an object to awareness, whether by volition (James, 1890) or through capture by visually salient regions of visual input (Helmholtz 1898, translated 1924). Attention is an inherently limited resource because the increase in firing rate required at the neuronal level is metabolically expensive (Attwell and Laughlin, 2001). One solution to this limitation is serially shifting attention where the driver would only attend to an object as it becomes necessary to do so. However, attending to an entire scene is not necessary (Li et al., 2002) to glean information at a global level. This global information is necessary to predict what objects in the scene may do in the future, which is the core of higher order situational awareness (Endsley, 1988).

Driving cannot be conceived of in the absence of vision – the driver *must* be able to perceive their operating environment. Understanding how the driver perceives the world around the vehicle, and how to assess what the driver can and cannot perceive is essential to understand what the driver does and why. The UFOV as a test and the Useful Field as a concept simplify this complex problem and aid in operationalizing behavior to facilitate research. While useful, we believe that the UFOV and the Useful Field have encouraged intuitions about visual perception that could benefit from integration with recent work in basic vision science. In this paper, we will discuss the UFOV and the Useful Field, how they have been used and modified in recent years, how they succeed and how they fail, and how their failures have been addressed in recent literature. Having done this, we will then discuss recent findings and theories from the basic vision science literature which indicate greater capabilities for peripheral vision than the Useful Field suggests, and how we believe that basic research can improve research and theory with which we understand driving going forward.

2. The UFOV and Useful Field in applied driving research

To begin, we will first provide a brief overview of the UFOV itself, so that we can operate from a place of common understanding (2.1). With that in hand, we will discuss how the UFOV has been used in applied driving research since its initial publication in 1993 (2.2), then discuss the limitations of the UFOV and the idea of the Useful Field (2.3). This section will conclude with a discussion of applied research which has recognized limitations of the UFOV and the narrow Useful Field interpretation respectively (2.4), and how this work has addressed some of the aforementioned shortcomings.

2.1. A brief overview of the UFOV

The common UFOV test (Ball and Owsley, 1993; Clay et al., 2005) uses three visual tasks to allow the researcher to map a subject's “useful” field, a region of visual space in which attending to objects is easy (but not perfect). First, the subject's ability to identify a foveal stimulus in the absence of other stimuli is determined (UFOV Subtest 1). Second, a peripheral localization task is performed in conjunction with a simultaneous foveal identification task (UFOV

Subtest 2). Third, the same dual task is performed (peripheral localization and foveal identification), with the complication that the foveal target is surrounded by distractor stimuli (UFOV Subtest 3). In UFOV Subtests 2 and 3, the duration and eccentricity of stimuli are manipulated to obtain a given level of detection performance. These approximate, to a degree, the driver's ongoing task of maintaining a representation of the forward roadway, while simultaneously detecting changes in the periphery. As originally described, the UFOV test was part of a larger battery of visual assessments (Ball and Owsley, 1991; Bowers et al., 2005; Owsley et al., 1991), and explicitly evaluated a drivers' ability to attend to single and multiple targets. The UFOV test certainly assesses drivers' ability to attend to different areas of the visual field within the spatial extent of the test itself, but does not, by any means, assess the entire visual field, nor is it designed to, although it can and has been used in concert with other assessments (Matas et al., 2014).

2.2. Driving research with the UFOV and Useful Field

Unlike perimetric tests used in clinical assessments of peripheral vision, the UFOV test does not require specialized equipment; the modern implementation of the test (from Visual Awareness) requires nothing more esoteric than a personal computer. Given this, it is no wonder that the UFOV assessment has been widely adopted in driving research, with more than three thousand papers having used or referenced it since its initial release as a commercial assessment in 1993 (per Google Scholar). Of particular relevance to the driving research community, the size of the Useful Field has been shown to decrease with age in subjects without other visual pathologies (Ball and Owsley, 1991, 1993; Ball et al., 2010; Clay et al., 2005; Owsley, 1994). Perhaps most intriguingly, decreases in the size of drivers' Useful Field correlate with their likelihood of automobile accident involvement (Ball et al., 2010; Ball and Owsley, 1991; Clay et al., 2005; Owsley, 1994; Owsley et al., 1991). This suggests that the UFOV test is a powerful tool for assessing drivers' visual capabilities, and has a role in research and assessment.

2.3. Limitations of the UFOV and the Useful Field

The UFOV is a simple, easily administered assessment, with considerable predictive power, but it is not without limitations. First, most UFOV assessments only test peripheral targets up to 20-30° eccentricity (Fig. 1), and thus do not report a Useful Field measurement larger than that testable extent (Ball et al., 1988). Assessing subjects' ability to allocate attention within this range has proven remarkably useful, but even a 30° radial range is considerably smaller than the entire extent of the visual field. Second, the UFOV test measures goal-directed attention to localized targets, rather than more broadly assessing what peripheral information subjects can acquire or use. The test was designed to study divided attention to a pair of foveal and peripheral objects, in order to capture effects anecdotally reported by subjects (e.g., that they were surprised by objects moving into their central field, as discussed by Ball and Owsley (1993)). However, in doing so, it exclusively focuses on subjects' ability to attend to *objects*. Processing individual objects, particularly in the periphery, comprises a limited subset of visual processing. While such tasks are useful in a driving context, the test is neither exhaustive nor intended to be so.

However, in the two decades and more since Ball and Owsley's seminal paper, the UFOV has evolved, enabling myriad new investigations of visual attention in driving. However, these more recent adaptations (Dobres et al., 2013; Oxley et al., 2013; Wolinsky et al., 2011), have moved to a laptop-based version of the UFOV, and use an even smaller 15-20° range than the original (1993) assessment. The great benefit of this shift to a more portable assessment

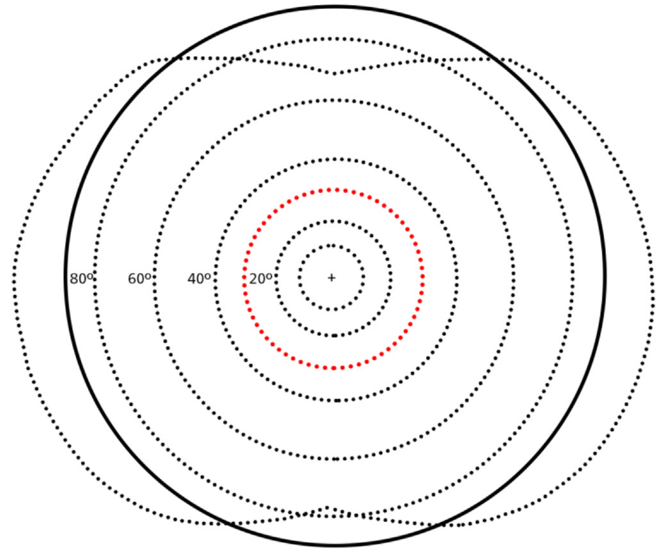

Fig. 1. A comparison of the human binocular visual field (based on the work of Traquair (1927); the mapped visual field is represented by the bow-tie shaped outline) with the range of the Useful Field of View task scaled appropriately. The innermost dotted ring is 10° radially from the point of fixation; the fovea and parafovea would be 3° radially at most. The red circle marks 30° of eccentricity from the fovea, the size of the Useful Field of View assessment region as described by Ball and Owsley (1993). The solid black circle is 90° radially from the point of fixation. Note that the binocular visual field extends to nearly 70° above the fovea, 80° below, and in excess of 100° to the left and right, far beyond the range assessed by the UFOV test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(versus the standalone Visual Attention Field Analyzer used previously (Ball and Owsley, 1993)) has been that a wide variety of studies have become possible, particularly examining the extent to which the Useful Field can be improved with training inside and outside the laboratory.

This shift has allowed the assessment to go to the subject, rather than the subject needing to come to the assessment, which has facilitated studies of how the Useful Field changes with training. The history of the UFOV and the Useful Field that it measures has shown that Useful Field performance improves with training (Ball et al., 1988), and there is some evidence that this training has some benefits on the road (Ball et al., 2010; Ball and Owsley, 1993), although the generalizability of these results has been questioned (Rabipour and Raz, 2012). However, it has also been suggested (Ball et al., 2010; Ball and Owsley, 1993; Clay et al., 2005; Owsley, 2011) that training drivers to look and attend more broadly may be more effective, since task-specific learning is often difficult to transfer to a new task (Rabipour and Raz, 2012).

2.4. Driving research addressing limitations of the UFOV and the Useful Field

Though the UFOV has been widely adopted, the driving research community has been aware of its limitations. We noted that the UFOV covers a limited spatial extent compared to the whole visual field, and some recent work has addressed this issue. In addition, the Useful Field has been shown to change based on task and gaze location. One study adapted the classic UFOV task to cover a much greater spatial range – out to 70° (Itoh et al., 2009). Their results record Useful Fields up to 40° radial extent in some conditions; much larger than the 15-20° radial extent normally measured. While such a large display (or equivalently, such a short viewing distance) is comparatively impractical for general purpose UFOV testing, these results do suggest that the Useful Field may not be constant across testing parameters and spatial range. Along these lines, recent work with the gaze-contingent UFOV (Gaspar et al., 2016) allows subjects to move their eyes, and suggests that the Useful Field may change dynamically depending on task and, potentially, on gaze location within the driving scene. This variability in measured Useful Field extent suggests that while Useful Field size correlates with on-road behavior, a single measurement of the Useful Field should not be treated as definitive. The extent of a driver's Useful Field appears to vary based both on the spatial range of the test, and on the task(s) they are asked to perform as part of the assessment.

Furthermore, Crundall et al. (1999) offer evidence that disputes the narrow interpretation of the Useful Field – that it is the only region of visual input processed. They advocate an understanding of the Useful Field and the region of visual space beyond it that is not dichotomous. Their work examined subjects' ability to detect hazards in video clips of road scenes, and they found a decrease in detectability of hazard cues with increased eccentricity, but no evidence for a hard cutoff, as suggested by the narrow perspective on the Useful Field. They advocate a dynamic view of the Useful Field, echoing the more recent work of Gaspar et al. (2016), suggesting that thinking beyond the Useful Field is essential to understand what the driver can and cannot perceive in their environment. Simply put, the mapped Useful Field should not be taken to be an aperture of perfect vision beyond which all is useless, and there is increasing evidence in the driving literature in support of this view.

3. Vision from a basic science perspective

To communicate our understanding of peripheral vision from a basic vision science perspective, this section will review recent research and theory on peripheral vision, and discuss how this work relates to the questions we set out in the introduction. To begin, we will discuss what recent research has shown peripheral vision to be capable of, and a state-of-the-art theory of peripheral vision (3.1). Since the UFOV test also addresses divided attention, we then move on to a discussion of visual attention, and its role (or lack thereof) in a modern conception of peripheral vision (3.2). We will then discuss why a modern understanding of peripheral vision poses significant challenges for a Useful Field-focused view of vision (3.3) and end with a discussion of what we believe peripheral vision is useful for in the broad context of driving (3.4).

3.1. Peripheral vision: capabilities, limitations and theory

For clarity, this section is divided into a review of what peripheral vision can and cannot do (3.1.1) and an overview of a modern theory of peripheral vision which accounts for recent experimental results, and, we believe, can inform a more complete understanding of peripheral vision in driving (3.1.2).

3.1.1. Capabilities and limitations of peripheral vision

Peripheral vision, as we have previously mentioned, is different from foveal vision – there are anatomical differences beginning in the retina, as well as differences in how peripheral input is represented in the brain. However, the fact that peripheral vision is not the same as foveal vision does not limit the usefulness of the information acquired from peripheral vision for activities such as driving. To begin with, the decrease in acuity with increased eccentricity, which is quite moderate to begin with (Anstis, 1974), does not cripple tasks which are performed with peripheral vision.

Research has shown that observers can process visual scenes more quickly than they can make an eye movement; in fact, one can acquire a basic understanding (gist) of a scene in less than 100 ms (Greene and Oliva, 2009; Oliva, 2005; Oliva and Torralba, 2006), a process which would be impossible without peripheral vision. Getting the gist of a scene does not require attending to objects within the scene (Fabre-Thorpe, 2011). Rather, observers can get the gist in a glance too short to shift attention (Thorpe et al., 1996), and even when attention is divided between the scene task and other tasks (Li et al., 2002). A single glimpse at a scene is sufficient because peripheral vision is immensely capable of informing higher order understanding.

Among its other uses, peripheral information is good for estimating the average feature value (e.g. average size) of a set of similar items, a process usually referred to as *ensemble coding* of visual features or ensemble perception. Critically, ensemble perception is entirely dependent on peripheral information; ensemble representations of emotion can even be generated in the complete absence of foveal information (B.A. Wolfe et al., 2015). The ability to estimate ensemble properties gets at an underlying truth of peripheral vision, namely that while it acquires a great deal of information, it does this at the expense of detailed information for each individual object (see Fig. 2a for an example). This ability to extract ensemble properties has been shown for a wide variety of stimuli (object size, (Ariely, 2001), object orientation, (Dakin and Watt, 1997), and even the average emotion of a group of faces (Haberman and Whitney, 2007; Yamanashi Leib et al., 2014)). A particularly notable example in a driving context is the ability to extract mean pedestrian heading (Sweeny et al., 2013). Peripheral vision enables the visual system to, for example, obtain a useful average of a group of similar items – whether they are pedestrians walking *en masse*, or the size of rocks on the road – but at the expense of identifying *individuals* within this group.

Peripheral objects are particularly difficult to identify in the presence of visual clutter, a phenomenon usually referred to as *visual crowding*. When there are multiple objects near each other in the periphery, they become difficult to *identify*, but they remain *detectable* (Bouma, 1970; Whitney and Levi, 2011). Crowding makes it difficult for a driver to distinguish various dials in a vehicle's instrument console when looking at the forward roadway, though they maintain visual awareness of the dials' general location. Crowding also makes it difficult to read a GPS system while keeping one's eyes on the road. Crowding is a problem of visual processing, not of the resolution of the retina – even quite far in the periphery, visual acuity is sufficient to read isolated small text (Anstis, 1974) – but in the world, surrounded by other objects, the name on a street sign becomes impossible to read (Fig. 2b). Note that neither acuity nor crowding are precipitous decay functions; rather, they are gradual and linear with eccentricity from the point of gaze. While some information from the periphery is lost, quite a bit is retained, and is available to other visual processes, including that which is used to perceive the gist of a scene. Examples of this retained information in driving include whether a right turn lies ahead, what city the driver is in, distinguishing a parking lot from an urban street, and identifying locations for an object like a stop sign (Ehinger and Rosenholtz, 2016). The driver may not be able to read a street sign when it is in his or her periphery, but can maintain a sense of its general location, and shift the point of gaze to read it. In fact, the act of planning this eye movement makes the crowded object more identifiable immediately before the eye moves (B. A. Wolfe and Whitney, 2014), suggesting that there is more than

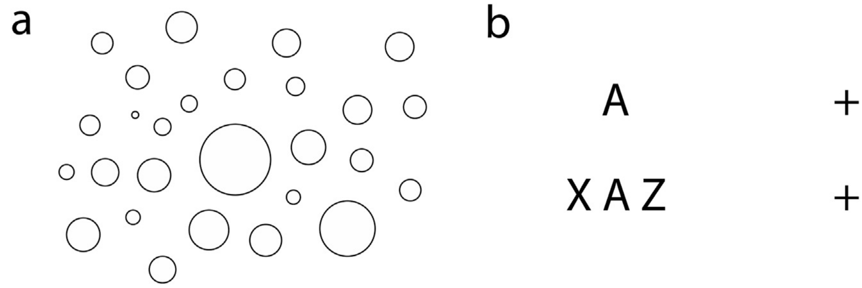

Fig. 2. Illustrations of ensemble perception and crowding. (a) Ensemble perception is your ability to determine the average size of the circles in this figure at a glance; as we discuss in the text, this is not limited to simple features, and requires peripheral vision. (b) If you fixate the cross to the right of the letters, you will notice that the A without letters around it is easy to read, while the A below it, flanked by X and Z, is much harder to read. While this is illustrated with letters for simplicity, crowding occurs between any and all objects in peripheral vision.

sufficient information not only to guide eye movements, but to facilitate perception of the world in their absence, or in the absence of covert attention to an eccentric object.

3.1.2. The Texture Tiling Model, a modern theory of peripheral vision

The periphery has enough detail to allow observers to direct their subsequent actions – but how does the visual system represent the periphery as a whole? Current theory suggests that, in doing so, the brain sacrifices irrelevant detail, while retaining sufficient information to facilitate much of what we commonly think of as vision – and to direct later action. This is accomplished through textural compression, which is a critical component of the Texture Tiling Model, developed by Rosenholtz and colleagues (Balas et al., 2009, 2011; Rosenholtz, Huang and Ehinger, 2012a; Rosenholtz, Huang, Raj, Balas and Ilie, 2012b). This model implies a much more complex role for peripheral vision, explain the results and phenomena thus far discussed and do so without relying on attention to the degree that earlier models did. As we will discuss, in many cases what once was considered the domain of attention can be explained by the nature of peripheral representations themselves (Rosenholtz, 2016), removing the need for attentional binding as required by earlier theories (Treisman and Gelade, 1980).

The Texture Tiling Model of peripheral vision suggests that peripheral input is encoded in the brain via a set of summary statistics, in a sense compressing the input to reflect available resources. Effectively, sizeable swathes of local peripheral regions are efficiently encoded like *textures*, rather than trying to maintain representations of each and every object in the world. For example, when one is driving, there is no need to represent each leaf on a tree to the side of the road – representing the leaves as a single leaf texture, retaining much of the detail of the original objects, is more than sufficient. Such a compressed representation captures many of the important details of the original image – the fact that there are leaves on the tree – while losing some of the precise configuration of the details (as shown in Fig. 3). Such a representation can explain the inability to identify crowded objects in the periphery, because their details are compressed to save capacity.

Consider that the driver does not need to represent each surface in the world with high fidelity. The small details of the road environment are not relevant to her need to drive safely. A compressed representation spares capacity for more critical needs. That a car is present in the next lane is relevant, but less important is what model of car. In essence, the Texture Tiling Model suggests that the visual periphery is represented by summarizing, but not collapsing, each texture in the scene, and representing it with a rich set of summary statistics that serve to capture quite a bit about the appearance of that "texture", rather than trying to represent it in consciously available detail. This retains much of the information available, but at the expense of some detail and some spatial fidelity. So, the car in the next lane is still visible, but it does not have the same detail that it would if the driver were to gaze directly at it. In essence, much of the information from the scene is present but not readily accessible to conscious mental processes. Oftentimes, knowing that the information originated from a general spatial location is good enough to direct further action.

The Texture Tiling Model also enables visualizations of how the brain might represent peripheral input, and thus gain an intuition for what the available information allows us to accomplish. Outputs from the Texture Tiling Model appear distorted. The distortion represents portions of the image that are ambiguous or unclear due to compressed peripheral representation. Looking at examples (Fig. 3), we can see that the model suggests that peripheral vision retains much of the information required for human observers to perform many visual tasks (e.g., visual search). The representations of peripheral information are imperfect, but far from useless. These visualizations also hint at why the measured Useful Field may depend on the stimulus and peripheral task: the utility of the available information, according to the Texture Tiling Model, depends upon both task and stimulus complexity.

To look at this through the lens of visual search, when looking for the correct button on the center console to turn the heat on, you need to have a sense of where to look, and the representation of the world from peripheral vision provides enough information to make a useful eye movement. These peripheral representations are capable of supporting perceptual learning even when the subject is unaware of the stimulus (Watanabe et al., 2001), and allow for the rapid perception of natural scene gist in the absence of eye movements or shifts of attention (Ehinger and Rosenholtz, 2016; Le Hoa Võ and Wolfe, 2015; Oliva, 2005). Given this, peripheral vision, as different as it is from foveal vision, is much more capable than often supposed, and we have yet to fully understand all that can be done with peripheral vision alone.

3.2. Attention, inattention and visual perception

Having discussed the capabilities of peripheral vision in general, we will now turn to attention as a concept within vision science, including a discussion of its basic properties, how it has been previously thought of in larger theories of perception, how we think of it now, and how vision operates both with and without attention.

3.2.1. Considering attention

The question of visual attention and its role in visual perception is an essential one. These questions have been asked since the inception of modern vision science (in the 19th century; c.f.

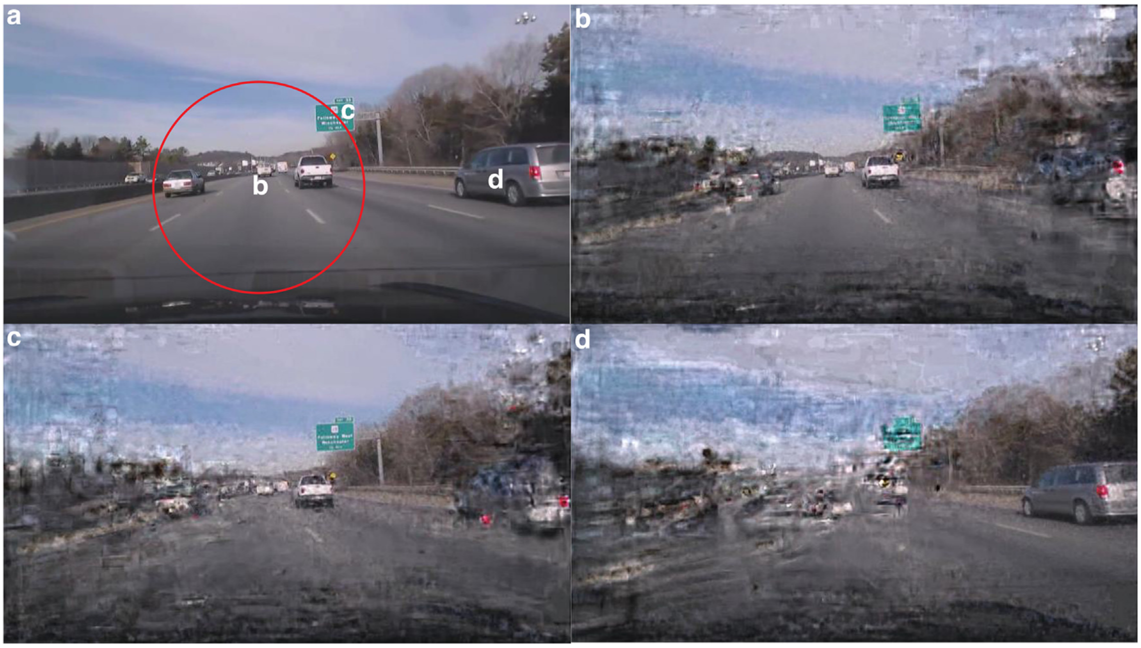

Fig. 3. Visualizing the information available in peripheral vision depending on fixation location. (a) An unmodified photograph of a highway scene near Boston, MA with an exit sign. The red circle around the letter b in the panel visualizes a 15° radial Useful Field of view. The letters b, c and d overlaid on the image indicate different fixation locations used for the visualizations in subsequent panels. (b) Photograph from (a), with the point of fixation on the forward roadway ahead of the vehicle, after being processed through the Texture Tiling model to visualize how peripheral information might be represented. Notice the degree to which the scene remains generally recognizable, and how the visualization changes with increased eccentricity from the leading vehicle. Also, note that the region corresponding to the Useful Field (as shown in (a)) is not left inviolate by this transformation. In particular, the exit sign remains recognizable, and the positions of other vehicles remains fairly stable, although some details are lost. (c) Photograph from (a), visualized with the point of fixation on the exit sign; notice that vehicles in the left lane are somewhat obscured, but detectable. There are considerable cues for lane-keeping, including the left road edge, which lies far from the point of gaze. (d) Photograph from (a), visualized with the point of fixation on the van in the far right lane. The exit sign is still visible, but the left lanes of travel are nearly unrecognizable, predicting suboptimal performance localizing nearby vehicles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Helmholtz, 1898, translated 1924; James, 1890)). The presumed role of attention in vision (and what, in vision, can be accomplished without it), has evolved as a result of over a century of research (see (Carrasco, 2011) for a modern review of recent work).

It had been previously theorized that attention was the linchpin that allowed us to perceive objects. Treisman's Feature Integration Theory (Treisman and Gelade, 1980) posited that perceiving objects required attention to bind their disparate visual features together, and that in the absence of attention to a given object, the representation reverted to jumbled features. The narrow Useful Field theory has no doubt been influenced by this theory of attention; in both theories, little perception occurs in the absence of attention. However, it is also worth noting that classic theories of attention (e.g., Feature Integration Theory) suggest even less perception in the absence of attention than does Useful Field theory. In fact, detailed perception in classical attentional theory is often thought to be limited to the presently attended object, rather than a larger range around the current point of fixation.

However, recent research has called into question the role of attention in visual perception in a number of ways. Behavioral research has shown that complex scenes and their contents can be perceived faster than this theory allows (Li et al., 2002). Furthermore, Feature Integration Theory was based on results from visual search experiments, in which search was presumed to be slow due to the need to serially shift attention to bind features. More recent work has suggested instead that due to confounds in those experiments, we cannot take difficult search to imply that attention is needed to bind features and perceive objects (Rosenholtz et al., 2012b). In fact, many visual phenomena that were once considered to be due to attentional mechanisms can instead be attributed to the intrinsic nature of peripheral vision and how peripheral information is represented in the brain (Rosenholtz, 2016). In turn, this suggests that much of vision is not gated by attention, and a great deal of perception can be achieved in its absence. This includes perception both at the fovea and in peripheral vision. Given current thinking, a modern account of vision places less weight on serial attention to objects in the scene, and a greater weight on the capabilities of peripheral vision even in the absence of selective attention.

3.2.2. Inattentional vision

The majority of vision occurs without serial selective attention to individual objects; there is simply too much information and not enough time for all of perception to be managed by serial attentional processes that only identify one object at a time. Selectively attending to objects in the world is a time-intensive process (Carlson et al., 2006), and while you can attend to multiple objects at the same time (Cavanagh and Alvarez, 2005), the number of objects in most environments exceeds the number of objects that can be tracked together. While selective attention is limited, being able to attend to objects when needed is useful to identify them, but identifying individual objects is not always necessary or useful.

What happens in the absence of selective attention, or when attention is focused on another task? Perhaps the best known result here is the tendency to miss an irrelevant gorilla in the center of the visual field (as memorably shown in the classic work of Simons and Chabris (1999)). Although gorillas are uncommon on the road, it is entirely possible to miss a dramatic change in the driving environment if otherwise occupied (c.f., (Rumar, 1990; Strayer et al., 2003)). While it is possible to safely navigate the world and avoid obstacles when attention is directed elsewhere (Tractinsky and Shinar, 2008), the details of these obstacles are likely to remain unnoticed, even if notionally relevant (Hyman et al., 2014). In addition, a variety of tasks have shown that people can integrate information from across the visual field in the absence of selective attention to individual elements (Haberman and Whitney, 2012; Oliva, 2005), showing that the visual system does not rely on selective attention for all of perception. Selective attention is quite limited, but observers are remarkably capable of using visual information in its absence to navigate the world – even if they miss the occasional unicycling clown (Hyman et al., 2010).

The vast majority of vision is a non-attentive process, and this fact is what allows people to perform other tasks simultaneously, such as driving. It is critical that people attend to objects in the world when they need to, but at the same time, the ability to perceive the world in the absence of attention is essential. Selective attention is, itself, imperfect, as shown by the phenomenon of drivers looking but not seeing (or, as we would have it, perceiving) relevant objects in the world. The UFOV assesses drivers' ability to selectively attend to objects, which is a critical component of their ability to perceive their environment, but this is only a subset of how the driver acquires the information they need. The fact that Useful Field extent is correlated with driver behavior makes it a useful tool, but not a universal explanation of vision in the context of driving. It is essential to understand that selective attention is not the sole determinant of perception, and that the vast majority of vision operates in its absence.

3.3. Against a narrow interpretation of the Useful Field

The Useful Field is an immensely appealing concept, and a deeply intuitive one. However, the narrow interpretation, where visual input from outside the Useful Field is not thought to be processed, is at odds with more recent work in human vision. This narrow conception of the Useful Field bears considerable resemblance to ideas that were pervasive in basic vision science until fairly recently. Many basic researchers once considered foveal vision (and a small region surrounding the fovea, not dissimilar in extent to the Useful Field) as the only truly useful portion of the visual field. This was often paired with the view that unattended vision (which often meant peripheral vision) had access to only a jumble of image features incapable of supporting more than the most crude sort of recognition (Treisman and Gelade, 1980). In other words, this theory implied that peripheral vision was of little use without attention. This view, while inaccurate by our current understanding, had a certain appeal, dovetailing as it did with both the notion of attention as necessary for detection, inherent in narrow Useful Field theory, and reports of "tunnel vision" under extreme stress (c.f., (Mackworth, 1965; Ringer et al., 2016; Williams, 1985, 2009)).

In contrast, we advocate a more nuanced approach to the Useful Field and peripheral vision more broadly. Thinking of the Useful Field as a hard boundary defining a region of useful or even perfect vision, while simple and appealing, is incorrect. This is apparent from our visualization of a road scene in Fig. 3, where fine details are degraded well within the Useful Field, but sufficient information is preserved to be useful throughout the image. However, objects at any significant eccentricity will also be unidentifiable due to crowding (Whitney and Levi, 2011), and will require an eye movement, rather than covert attention, to identify them (Harrison et al., 2013; B. A. Wolfe and Whitney, 2014).

In addition, Useful Field extent is variable depending on task and stimulus properties (Gaspar et al., 2016; Itoh et al., 2008). While the Useful Field, as measured with a specific task, might indicate a region of space where selective attention is easy *for that task*, talking about the Useful Field as if it were invariant across task and tested extent is inaccurate. Crundall et al. (1999, 2002), in their work on drivers' ability to detect hazards on the road, do not find evidence for a hard limit on visual perception. As a result, they, like us, advocate for an understanding of the Useful Field as a region wherein it is easier for the driver to notice relevant changes, yet outside of which it remains entirely possible to notice those changes.

In considering visual perception in driving, we would move away from a singular focus on what the driver has attended to in the scene, and towards a more holistic understanding of how the driver perceives the scene. Understanding how the periphery is represented, as described by the Texture Tiling Model, facilitates this new understanding, because these holistic representations are sufficient to perform many tasks required for driving. Considerable evidence suggests that human observers – including drivers – receive a great deal of detailed information from throughout the visual field, not just within the Useful Field, and that this information is available to support safe driving. Critically, selective attention to objects plays a smaller role than previously thought in this larger process. In addition, using the Texture Tiling Model in interpreting the results of UFOV assessments and naturalistic driving may facilitate more complete explanations of successes and failures in a given task.

3.4. Reflections on peripheral vision and its role in driving

In addition to recent developments in basic vision science, which lead to a different and deeper conception of the capabilities, limitations, and mechanisms of peripheral vision, relevant work on the utility of peripheral vision has also appeared in applied research. It would be a rare theory or experiment in the applied literature that did not ascribe at least some capabilities to peripheral vision, if only at the level of peripheral vision being useful for lane keeping (Mourant and Rockwell, 1972; Summala et al., 1996). Applied work has shown that drivers can detect brake lights in the periphery far beyond the driver's Useful Field, and in fact out to the limits of the visual field (Lamble et al., 1999; Yoshitsugu et al., 2000). Work by Crundall and colleagues has examined drivers' ability to perceive hazards in road scene video away from their point of gaze (1999, 2002). Their results show that even complex information, which cues a driver to an emergent hazard, can be perceived outside the Useful Field. As a result, they advocate for a more unified understanding of the Useful Field and the more eccentric regions of the visual field.

Given basic human vision research into the capabilities of peripheral vision for scene perception, as well as predictions of the Texture Tiling Model as to what information is available for scene tasks, a fruitful topic for future work in the applied literature is consideration of peripheral vision in the context of situational awareness and its development (Endsley, 1988; Smith and Hancock, 1995). This question has become particularly important in light of two recent developments, namely the greater potential for drivers to distract themselves by engaging with a mobile device (e.g., a smartphone), and the advent of partially automated vehicles which permit the driver to not attend as closely to the operating environment, but, in turn, demand that the driver take over when needed. The impact of distraction on drivers' situational awareness has been the focus of considerable research (Kass et al., 2007; G. Underwood, Ngai and Underwood, 2013; Young et al., 2013), indicating that distraction reduces drivers' awareness of their environment. We would add a new thought here – a distracted driver, particularly one who is attending to a mobile device rather than to the road – is, as a result, attempting to develop situational awareness *with peripheral input alone,* because their point of gaze prevents them from using central vision to acquire information from the environment outside the vehicle. Understanding what peripheral vision can and cannot do is essential to understanding how awareness is constructed from all available visual input.

Similarly, the question of how long a driver of an automated vehicle needs in order to develop situational awareness when called upon to do so (Lu et al. 2017) also requires an understanding of what visual information is available to the driver. Measuring situational awareness is a considerable challenge in its own right, but in order to both measure it and to theorize about it, researchers should first acquire a deep understanding and appreciation of how drivers' visual systems can and cannot acquire information, and how that information is represented. With this in hand, essential future work on situational awareness and drivers' ability to represent the world around them will better represent drivers' actual capabilities and limitations, and facilitate design and policy that is cognizant of these factors.

4. Conclusions

The UFOV, as a tool for assessing visual attention within a limited portion of the visual field, provides an accessible means to examine a critical aspect of driving in vision – namely, drivers' ability to attend to objects entering the center of their visual field while nonetheless noticing objects in their periphery. The Useful Field, as measured by the UFOV test, encourages an intuition that peripheral vision is not terribly important – that drivers might as well be contending with tunnel vision with a radius of 15–20°, and perhaps a few global motion cues, like optic flow (useful for lane-keeping), in the periphery beyond (Mourant and Rockwell, 1972). While there are certainly differences between central and peripheral vision, both in terms of the information available and how that information is represented, it was our goal to expand the consideration of visual input, as it were, to include the entire periphery, not simply the portion defined as useful. We are not advocating that the applied research community discard either the UFOV as a test or the Useful Field as a concept, but rather that, in light of recent work in basic vision science research, that their use be reconsidered in the context of our increasing understanding of the capabilities of peripheral vision.

We have three core recommendations that build on and extend the understanding of visual perception implicit in the use of the UFOV as a primary assessment. The UFOV is an assessment of visual attention within a specified region of space, but attention is a limited resource, and is not and cannot be the only process which serves the driver's perception of the road environment. The UFOV should be used in cognizance of the fact that a driver's situational awareness is built on a foundation of unattended input, and that the UFOV does not assess the driver's ability to acquire this essential information. Related to this, the UFOV is a test of the central portion of the visual field, and while much useful information does appear in this region, much does not. Therefore, future considered use of the UFOV should be aware of this limitation and use the UFOV in concert with a more wide-ranging assessment of the visual field. Using the UFOV as a primary selection tool, to determine whether a person's innate capabilities predispose them to being skilled at a given vehicular task is problematic, given its inherent limitations. We believe the UFOV should continue to be a tool in a wide range of applied contexts, but it should not be thought of as a universal answer for questions of visual perception in driving. It is a useful tool for assessing visual capabilities in a subset of the visual field, but selective attention is not all of vision, nor can a test of it be a comprehensive assessment.

Understanding peripheral vision beyond the spatial scope measured by the UFOV is of increasing importance given the vast changes underway in the driving experience. The shift towards increased automation in the vehicle will result in increasing periods of time when the driver is oriented well away from the roadway, rendering it imperative that we consider the capabilities and limitations of vision throughout the entire field of view. In particular, the focus of the UFOV on selective attention, while important, ignores the fact that much of visual information acquisition and processing does not require attention. The efficient allocation of attentional resources requires a robust representation of the entire visual field, and this representation on its own enables the performance of many tasks without requiring attention. Peripheral vision has its own strengths and weaknesses, but there is a great deal more information available than our intuitions about vision might suggest. The recent development of the Texture Tiling Model suggests a way forward – if we can begin to consider how the periphery is represented, we can consider what information is available to the driver, and how the nature of peripheral vision may explain driver behavior and performance.

Building on this, we would argue that responding to situationally relevant events and maintaining complete basic operational control is often accomplished without top-down attention to every element of the scene. In short, drivers may not be aware of the location and identity of an object outside their Useful Field, but their visual system has nonetheless processed a great deal of useful information, and the resulting representation of the world is sufficient, in many cases, to guide action. As the world begins to transform from one of manually controlled automobiles (that require some level of continuous attention to the forward road) to more automated vehicles, a more detailed understanding of the capabilities of the peripheral visual field may be essential to understanding a driver's ability to maintain a sufficient level of situational awareness. In summary, the role of peripheral information in the driver's development of awareness may be an important consideration going forward, particularly in the design of interfaces aiming to enhance this awareness.

Our goal in writing this paper was to build on the foundation that the widespread use of the Useful Field and the UFOV has created in driving research, and to introduce a wider audience to recent work in vision science that has come to consider the role of peripheral vision in a new light. Our hope is that by introducing these findings and theories to a new audience that they will foster a new appreciation for the complexities and capabilities of peripheral vision, encompassing what has been learned from the UFOV and the Useful Field, leading to more a complete understanding of the role of peripheral vision in situational awareness and safe driving.

Funding

Support for this work was provided in part by the US DOT's Region I New England University Transportation Center at MIT and the Toyota Class Action Settlement Safety Research and Education Program. The views and conclusions being expressed are those of the authors, and have not been sponsored, approved, or endorsed by Toyota or plaintiffs' class counsel. Additional support for this work was provided by the Toyota Research Institute/MIT CSAIL joint partnership.

References

Andersen, G.J., Ni, R., Bian, Z., Kang, J., 2011. Limits of spatial attention in three-dimensional space and dual-task driving performance. Accid. Analysis Prev. 43 (1), 381–390. http://doi.org/10.1016/j.aap.2010.09.007.

Anstis, S.M., 1974. Letter: a chart demonstrating variations in acuity with retinal position. Vis. Res. 14 (7), 589–592.

Ariely, D., 2001. Seeing sets: representation by statistical properties. Psychol. Sci. 12 (2), 157–162.

Attwell, D., Laughlin, S.B., 2001. An energy budget for signaling in the grey matter of the brain. J. Cerebr. Blood Flow Metabol. 36, 1133–1145. http://doi.org/10.1097/00004647-200110000-00001.

Balas, B., Nakano, L., Rosenholtz, R., 2009. A summary-statistic representation in peripheral vision explains visual crowding. J. Vis. 9 (12), 1–18. http://doi.org/10.1167/9.12.13.

Ball, K.K., Beard, B.L., Roenker, D.L., Miller, R.L., Griggs, D.S., 1988. Age and visual search: expanding the useful field of view. J. Opt. Soc. Am. a, Opt. Image Sci. 5 (12), 2210–2219.

Ball, K., Owsley, C., 1991. Identifying correlates of accident involvement for the older driver. Hum. Factors 33, 583–595. http://doi.org/10.1177/001872089103300509.

Ball, K., Owsley, C., 1993. The useful field of view test: a new technique for evaluating age-related declines in visual function. J. Am. Optometric Assoc. 64 (1), 71–79.

Ball, K., Edwards, J.D., Ross, L.A., McGwin, G., 2010. Cognitive training decreases motor vehicle collision involvement of older drivers. J. Am. Geriatrics Soc. 58 (11), 2107–2113. http://doi.org/10.1111/j.1532-5415.2010.03138.x.

Bouma, H., 1970. Interaction effects in parafoveal letter recognition. Nature 226 (5241), 177–178.

Bowers, A., Peli, E., Elgin, J., McGwin, G., Owsley, C., 2005. On-road driving with moderate visual field loss. Optometry Vis. Sci. 82 (8), 657–667. http://doi.org/10.1097/01.opx.0000175558.33268.b5.

Carlson, T.A., Hogendoorn, H., Verstraten, F.A.J., 2006. The speed of visual attention: what time is it? J. Vis. 6 (12), 6, 6. http://doi.org/10.1167/6.12.6.

Carrasco, M., 2011. Visual attention: the past 25 years. Vis. Res. http://doi.org/10.1016/j.visres.2011.04.012.

Cavanagh, P., Alvarez, G., 2005. Tracking multiple targets with multifocal attention. Trends Cognitive Sci. 9 (7), 349–354. http://doi.org/10.1016/j.tics.2005.05.009.

Clay, O.J., Wadley, V.G., Edwards, J.D., Roth, D.L., Roenker, D.L., Ball, K.K., 2005. Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: current and future implications. Optometry Vis. Sci. 82 (8), 724–731.

Crundall, D., Underwood, G., Chapman, P., 1999. Driving experience and the functional field of view. Perception 28 (9), 1075–1087.

Crundall, D., Underwood, G., Chapman, P., 2002. Attending to the peripheral world while driving. Appl. Cogn. Psychol. 16 (4), 459–475. http://doi.org/10.1002/acp.806.

Dakin, S.C., Watt, R.J., 1997. The computation of orientation statistics from visual texture. Vis. Res. 37 (22), 3181–3192.

Dobres, J., Potter, A., Reimer, B., Mehler, B., 2013. Assessing the Impact of "Brain Training" on Changes in Driving Performance, Visual Behavior, and Neuropsychology. Proceedings of the 7th Driving Assessment Conference, pp. 1–7.

Ehinger, K.A., Rosenholtz, R., 2016. A general account of peripheral encoding also predicts scene perception performance. J. Vis. 16 (2), 13, 13. http://doi.org/10.1167/16.2.13.

Endsley, M.R., 1988. Proceedings of the Human Factors Society. Design and evaluation for situation awareness enhancement, vol. 32, pp. 97–101.

Fabre-Thorpe, M., 2011. The characteristics and limits of rapid visual categorization. Front. Psychol. 2. http://doi.org/10.3389/fpsyg.2011.00243.

Gaspar, J.G., Ward, N., Neider, M.B., Crowell, J., Carbonari, R., Kaczmarski, H., et al., 2016. Measuring the useful field of view during simulated driving with gaze-contingent displays. Hum. Factors J. Hum. Factors Ergonomics Soc. 58 (4), 630–641. http://doi.org/10.1177/0018720816642092.

Greene, M.R., Oliva, A., 2009. The briefest of glances: the time course of natural scene understanding. Psychol. Sci. 20 (4), 464–472. http://doi.org/10.1111/j.1467-9280.2009.02316.x.

Gugerty, L., 2011. Situation Awareness in Driving. Handbook of Driving Simulation for Engineering, Medicine, and Psychology. CRC Press. http://doi.org/10.1201/b10836-20.

Haberman, J., Whitney, D., 2007. Rapid extraction of mean emotion and gender from sets of faces. Curr. Biol. 17 (17), R751–R753.

Haberman, J., Whitney, D., 2012. Ensemble perception: summarizing the scene and broadening the limits of visual processing. In: Wolfe, J., Robertson, L. (Eds.), From Perception to Consciousness: Searching with Anne Treisman. Oxford University Press, pp. 339–349.

Harrison, W.J., Mattingley, J.B., Remington, R.W., 2013. Eye movement targets are released from visual crowding. J. Neurosci. 33 (7), 2927–2933. http://doi.org/10.1523/JNEUROSCI.4172-12.2013.

Helmholtz, H., 1924. Treatise on Physiological Optics, vol. 3. Treatise on Physiological Optics.

Hyman, I.E.J., Sarb, B.A., Wise-Swanson, B.M., 2014. Failure to see money on a tree: inattentional blindness for objects that guided behavior. Front. Psychol. 5 (679). http://doi.org/10.3389/fpsyg.2014.00356.

Hyman, I.E., Boss, S.M., Wise, B.M., McKenzie, K.E., Caggiano, J.M., 2010. Did you see the unicycling clown? Inattentional blindness while walking and talking on a cell phone. Appl. Cogn. Psychol. 24 (5), 597–607.

Itoh, N., Sagawa, K., Fukunaga, Y., 2008. Useful field of view for older people. Gerontechnology 7 (2), 138.

Itoh, N., Sagawa, K., Fukunaga, Y., 2009. Useful visual field at a homogeneous background for old and young subjects. Gerontechnology 8 (1), 42–51.

James, W., 1890. Principles Of Psychology.

Kass, S.J., Cole, K.S., Stanny, C.J., 2007. Effects of distraction and experience on situation awareness and simulated driving. Transp. Res. Part F Traffic Psychol. Behav. 10 (4), 321–329. http://doi.org/10.1016/j.trf.2006.12.002.

Lamble, D., Laakso, M., Summala, H., 1999. Detection thresholds in car following situations and peripheral vision: implications for positioning of visually demanding in-car displays. Ergonomics 42 (6), 807–815.

Le Hoa Võ, M., Wolfe, J.M., 2015. The role of memory for visual search in scenes. Ann. N. Y. Acad. Sci. 1339 (1), 72–81. http://doi.org/10.1111/nyas.12667.

Li, F.F., Vanrullen, R., Koch, C., Perona, Pietro, 2002. Rapid natural scene categorization in the near absence of attention. Proc. Natl. Acad. Sci. U. S. A. 99 (14), 9596–9601. http://doi.org/10.1073/pnas.092277599.

Lu, Z., Coster, X., de Winter, J., 2017. How much time do drivers need to obtain situation awareness? A laboratory-based study of automated driving. Appl. Ergon. 60, 293–304. http://doi.org/10.1016/j.apergo.2016.12.003.

Mackworth, N.H., 1965. Visual noise causes tunnel vision. Psychonomic Sci. Psychonomic Sci. 3, 67–68.

Matas, N.A., Nettelbeck, T., Burns, N.R., 2014. Cognitive and visual predictors of UFOV performance in older adults. Accid. Analysis Prev. 70, 74–83. http://doi.org/10.1016/j.aap.2014.03.011.

Mourant, R.R., Rockwell, T.H., 1972. Strategies of visual search by novice and experienced drivers. Hum. Factors 14 (4), 325–335.

Oliva, A., 2005. Gist of the scene. Neurobiol. Atten. 251–256.

Oliva, A., Torralba, A., 2006. Building the gist of a scene: the role of global image features in recognition. Prog. Brain Res. 155, 23–36. http://doi.org/10.1016/S0079-6123(06)55002-2.

Owsley, C., 1994. Vision and driving in the elderly. Optometry Vis. Sci. 71 (12), 727–735.

Owsley, C., 2011. Aging and vision. Vis. Res. 51 (13), 1610–1622. http://doi.org/10.1016/j.visres.2010.10.020.

Owsley, C., Ball, K., Sloane, M.E., Roenker, D.L., Bruni, J.R., 1991. Visual/cognitive correlates of vehicle accidents in older drivers. Psychol. Aging 6 (3), 403–415.

Oxley, J., Langford, J., Koppel, S., Charlton, J., 2013. Seniors Driving Longer, Smarter, Safer: Enhancement of an Innovative Educational and Training Package for the Safe Mobility of Seniors.

Rabipour, S., Raz, A., 2012. Training the brain: fact and fad in cognitive and behavioral remediation. Brain Cognition 79 (2), 159–179. http://doi.org/10.1016/j.bandc.2012.02.006.

Ringer, R.V., Throneburg, Z., Johnson, A.P., Kramer, A.F., Loschky, L.C., 2016. Impairing the useful field of view in natural scenes: tunnel vision versus general interference. J. Vis. 16 (2), 7–25. http://doi.org/10.1167/16.2.7.

Rosenholtz, R., 2011. What your visual system sees where you are not looking. Proc. SPIE Hum. Vis. Electron. Imaging 7865–7910.

Rosenholtz, R., 2016. Capabilities and limitations of peripheral vision. Annu. Rev. Vis. Sci. 2 (1), 437–457. http://doi.org/10.1146/annurev-vision-082114-035733.

Rosenholtz, R., Huang, J., Ehinger, K.A., 2012a. Rethinking the role of top-down attention in vision: effects attributable to a lossy representation in peripheral vision. Front. Psychol. 3 (13). http://doi.org/10.3389/fpsyg.2012.00013.

Rosenholtz, R., Huang, J., Raj, A., Balas, B.J., Ilie, L., 2012b. A summary statistic representation in peripheral vision explains visual search. J. Vis. 12 (4). http://doi.org/10.1167/12.4.14.

Rumar, K., 1990. The basic driver error: late detection. Ergonomics 33 (10–11), 1281–1290. http://doi.org/10.1080/00140139008925332.

Simons, D.J., Chabris, C.F., 1999. Gorillas in our midst: sustained inattentional blindness for dynamic events. Perception 28 (9), 1059–1074.

Smith, K., Hancock, P.A., 1995. Situation awareness is adaptive, externally directed consciousness. Hum. Factors 37 (1), 137–148. http://doi.org/10.1518/001872095779049444.

Strayer, D.L., Drews, F.A., Johnston, W.A., 2003. Cell phone-induced failures of visual attention during simulated driving. J. Exp. Psychol. Appl. 9 (1), 23–32. http://doi.org/10.1037/1076-898x.9.1.23.

Summala, H., Nieminen, T., Punto, M., 1996. Maintaining lane position with peripheral vision during in-vehicle tasks. Hum. Factors J. Hum. Factors Ergonomics Soc. 38 (3), 442–451. http://doi.org/10.1518/001872096778701944.

Sweeny, T.D., Haroz, S., Whitney, D., 2013. Perceiving group behavior: sensitive ensemble coding mechanisms for biological motion of human crowds. J. Exp. Psychol. Hum. Percept. Perform. 39 (2), 329–337. http://doi.org/10.1037/a0028712.

Thorpe, S., Fize, D., Marlot, C., 1996. Speed of processing in the human visual system. Nature 381 (6582), 520–522. http://doi.org/10.1038/381520a0.

Tootell, R.B., Silverman, M.S., Switkes, E., De Valois, R.L., 1982. Deoxyglucose analysis of retinotopic organization in primate striate cortex. Science 218 (4575), 902–904.

Tractinsky, N., Shinar, D., 2008. Chi'08 alt.Chi/Do We Bump into Things More while Speaking on a Cell Phone? ACM, New York, New York, USA, pp. 2433–2442. http://doi.org/10.1145/1358628.1358700.

Traquair, H.M., 1927. Vol, first ed.. An Introduction to Clinical Perimetry. Henry Kimpton, VIII London, pp. 4–10.

Treisman, A.M., Gelade, G., 1980. A feature-integration theory of attention. Cogn. Psychol. 12 (1), 97–136. http://doi.org/10.1016/0010-0285(80)90005-5.

Underwood, G., Ngai, A., Underwood, J., 2013. Driving experience and situation awareness in hazard detection. Saf. Sci. 56, 29–35. http://doi.org/10.1016/j.ssci.2012.05.025.

Watanabe, T., Náñez, J.E., Sasaki, Y., 2001. Perceptual learning without perception. Nature 413 (6858), 844–848. http://doi.org/10.1038/35101601.

Whitney, D., Levi, D.M., 2011. Visual crowding: a fundamental limit on conscious perception and object recognition. Trends Cognitive Sci. 15 (4), 160–168. http://doi.org/10.1016/j.tics.2011.02.005.

Williams, L.J., 1985. Tunnel vision induced by a foveal load manipulation. Hum. Factors 27 (2), 221–227.

Williams, L.J., 2009. Peripheral target recognition and visual field narrowing in aviators and nonaviators. Int. J. Aviat. Psychol. 5 (2), 215–232. http://doi.org/10.1207/s15327108ijap0502_6.

Wolfe, B.A., Whitney, D., 2014. Facilitating recognition of crowded faces with pre-saccadic attention. Front. Hum. Neurosci. 8 (103). http://doi.org/10.3389/fnhum.2014.00103.

Wolfe, B.A., Kosovicheva, A.A., Leib, A.Y., Wood, K., Whitney, D., 2015. Foveal input is not required for perception of crowd facial expression. J. Vis. 15 (4), 11. http://doi.org/10.1167/15.4.11.

Wolinsky, F.D., Vander Weg, M.W., Howren, M.B., Jones, M.P., Martin, R., Luger, T.M., et al., 2011. Interim analyses from a randomised controlled trial to improve visual processing speed in older adults: the Iowa Healthy and Active Minds Study. BMJ Open 1 (2), e000225. http://doi.org/10.1136/bmjopen-2011-000225.

Yamanashi Leib, A., Fischer, J., Liu, Y., Qiu, S., Robertson, L., Whitney, D., 2014. Ensemble crowd perception: a viewpoint-invariant mechanism to represent average crowd identity. J. Vis. 14 (8). http://doi.org/10.1167/14.8.26.

Yoshitsugu, N., Ito, T., Asoh, T., 2000. JAMA's Safety Guideline on In-vehicle Display Systems (The study of monitor location of In-vehicle). Eye 1–7.

Young, K.L., Salmon, P.M., Cornelissen, M., 2013. Missing links? The effects of distraction on driver situation awareness. Saf. Sci. 56, 36–43. http://doi.org/10.1016/j.ssci.2012.11.004.