2 Visual Requirements of Vehicular Guidance

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CONTENTS

REFLECTION

We are interested in the very broad, yet deep, questions regarding the minimal visual requirements of driving an automobile. How does one begin such an enormous effort? Like many others, our search starts with a consideration of the evolutionary history of our species. Obviously, it makes no sense to ask how the demands of driving have influenced the evolutionary development of our visual system since the automobile has been in use for only a century. However, when we consider driving as "locomotion via technology" (to paraphrase a 1938 paper by Gibson and Crooks), we instantly arrive at a proposition that links the abilities of today's drivers to the contributions of the thousands of generations that have come before us. We can now easily

imagine how our visual systems might have evolved in order to meet the demands of terrestrial navigation and, thus, the driving task itself. Given the context of "driving as terrestrial locomotion" the ambient–focal dichotomization of the visual brain appears to us, and many others, to represent a natural construct upon which to build a visual theory of the driving task. This focus on the ambient–focal dichotomy also provides a powerful mechanism for conceptualizing another major interest of our laboratory; namely, the emerging visual information processing problems of older drivers. Presently, we believe that the proclivity of older drivers to suffer the now infamous "looked but didn't see" type automobile crash to be a manifestation of a diminished efficiency of the ambient visual system's ability to preemptively alert the focal systems as to the occurrence and general location of significant events in the peripheral field of view. Yet, the validity of this proposition—which we have named the *ambient insufficiency hypothesis* of visual aging—has yet to be rigorously tested. This, we hope, shall occupy the pages of book chapters to be published in the not too distant future.

2.1 INTRODUCTION

What are the visual requirements of driving? On one level, this is both an interesting and important question. However, on another level, it is simply too broad of a question to be answered given the current state of our knowledge. Instead, a simpler question will be addressed in this chapter; namely, what are the visual requirements of vehicular guidance. Even this question is not easy to answer given the current state of knowledge. To begin to do so, one needs both a theoretical framework that links observable aspects of steering performance to the rich database of contemporary vision science as well as a family of experimental protocols that can be used to test and refine the theory.

This chapter begins by introducing the reader to the ambient–focal dichotomization of visual functioning and shows how this approach provides a heuristic for contextualizing steering behavior within the domain of neurophysiological and psychophysical vision science. Next, a series of experimental studies that directly and indirectly support the validity of this theoretical framework will be explored. Finally, conclusions regarding current support for the ambient–focal heuristic are summarized together with some speculation regarding future research directions aimed at employing this framework to improve our understanding of visually guided driving behavior.

2.2 THEORETICAL FRAMEWORK FOR LINKING VISION AND DRIVING

Herschel Leibowitz and his colleagues have developed a linking hypothesis that provides a powerful heuristic for conceptualizing vehicle guidance behavior within the rich domain of vision science (see Leibowitz and Owens, 1977; Leibowitz, Owens, and Post, 1982; Owens and Tyrrell, 1999; Andre, Owens, and Harvey, 2002). This heuristic is based upon an anatomical and functional dichotomization of the visual

system into two parallel streams of processing, which have been labeled the *ambient* and *focal* subsystems. In order to more fully appreciate the potential utility of this ambient–focal dichotomy for driving research, it is first necessary to consider the origin and characteristics of this functional approach to describing the visual system.

2.2.1 Two Modes of Visual Processing: The Ambient–Focal Dichotomy

The proposition that visual processing proceeds along two parallel streams—one specialized for visual guidance through the environment (ambient system) and the other subsuming the functions of object recognition and identification (focal system)—can be traced back at least as far as the late 1960s. Numerous studies during this period demonstrated that visual functions related to spatial orientation (i.e., those required to answer the question "Where am I?") appeared to be heavily reliant upon subcortical pathways in the brain; while visual functions related to object recognition (i.e., those required to answer the question "What is it?") relied more heavily upon cortical levels of processing. The most direct illustration of this functional and anatomical dissociation of the processing of *what* versus *where* information can be found in the work of Schneider (1967; 1969). He trained hamsters to successfully perform a visual pattern discrimination task in order to achieve a food reward. When the primary visual cortex was surgically damaged in a subgroup of these mammals, Schneider noted that the animals maintained their ability to visually orient within the experimental apparatus despite the fact that they completely lost their ability to perform the visual form discrimination task. In another subgroup of these mammals, he surgically destroyed the subcortical visual pathway involving the superior colliculus while leaving the primary visual cortex intact. These animals lost the ability to visually guide their behavior in the experimental apparatus yet maintained the ability to perform the visual form discrimination task. Schneider had demonstrated a double dissociation between what he termed the *what* and *where* modes of the visual system. Around this same time, other researchers demonstrated a similar anatomical and functional dissociation within the visual systems of fish and amphibians (Ingle, 1967, 1973) as well as cats, monkeys, and humans (Held, 1968, 1970; Trevarthen, 1968). In fact, the terms *ambient* and *focal* (to denote the where and what visual subsystems, respectfully) were originally coined by Trevarthen (1968) who discovered a dissociation between the "vision of space" around the body and the "vision of things" within the environment based upon his work with "split-brain" monkeys.

The classical work, described above, attributed ambient (where) vision to subcortical pathways, while focal (what) vision was thought to be mediated by cortical pathways. However, more recent investigations suggest that a what–where functional dichotomy also exists in two anatomically distinct cortical pathways in the primate. Ungerleider and Mishkin (1982) identified two such pathways and called them the dorsal stream and ventral stream, respectively. Their dorsal stream interconnects the striate (primary) visual cortex, prestriate, and inferior parietal areas, and enables visual location behavior. Their ventral stream, on the other hand, interconnects the striate, prestriate, and inferior temporal areas, and enables the visual identification of objects (see Mishkin, Ungerleider, and Macko, 1983). Norman (2002) has provided a detailed history of the evolution of the ambient–focal construct and its subsequent

augmentation by the cortico–centric dorsal–ventral stream dichotomization of visual system along both anatomical and functional lines. He notes one final extension of the dorsal–ventral dichotomy based upon the work of Goodale and Milner (1992). This involves a subtle yet important modification of the allocation of the where function. For Goodale and Milner, the dorsal stream supports the visual control of guidance and motor behavior. As such, the dorsal stream operates using a framework rooted in egocentric coordinates which allow the organism to manipulate the environment and move through it (e.g., grasping and locomotion). The ventral stream remains principally involved with the recognition and identification of objects. Toward this aim, the ventral visual system must process some aspects of spatial information. However, its representation of spatial information employs an allocentric (rather than egocentric) framework. That is, the ventral system carries information about the relative position of objects with respect to one another. Hence, Goodale and Milner support that the ventral system represents space in the relative coordinates needed for the perception of object interrelationships, while the dorsal system represents space in body-centered absolute coordinates needed to support manual interaction with the environment (including locomotion by foot and vehicle).

2.2.2 Properties of Ambient (Dorsal) versus Focal (Ventral) Vision

The previous section reviewed the conceptual evolution of the ambient–focal dichotomization of the visual system into its more contemporary dorsal–ventral stream manifestation. In deference to the pioneering efforts of Leibowitz and his associates, and in order to maintain a consistency in the terminology employed in the surface transportation research literature, this report will continue to use the terms *ambient* and *focal* when referring to the parallel modes of visual representation and processing. Hereafter, any reference to ambient vision will subsume the properties of the dorsal stream, and references to focal vision will subsume the properties of the ventral stream.

In this section, the distinctive functional characteristics of the primate ambient and focal visual streams will be delineated and briefly discussed. These characteristics represent consensus views arising from a large body of physiological, neuropsychological, and psychophysical research and are summarized in Table 2.1. The ambient visual stream receives some input from subcortical areas such as the superior colliculus and the pulvinar region; however, its major source of input comes from magnocellular projections. Since it relies so heavily upon the magnocellular branch of the retino–geniculate–cortical pathway, several special functional characteristics may be attributed to processing within the ambient stream. That is, compared to the focal (ventral) stream, the ambient stream can be thought of as being: capable of resolving high temporal variations (i.e., motion and/or flicker), insensitive to high-spatial-frequency information, especially sensitive to low-contrast/low-spatial-frequency information, and insensitive to color contrast (Merigan and Maunsell, 1993; Fortes and Merchant, 2006). Input to the focal visual stream stems almost exclusively from the primary visual cortex and, unlike the ambient stream, depends heavily upon information from the parvocellular branch of the retino–geniculate–cortical pathway. This dependence upon parvocellular visual input indicates that

TABLE 2.1
Functional Characteristics and Response Properties of the Ambient and Focal Visual Systems

	Ambient System	Focal System
Primary functions	Visual guidance; motor control	Form recognition; identification
LGN (lateral Geniculate Nucleus) source	Magnocellular	Parvocellular
Cortical stream	Dorsal stream	Ventral stream
Field of view	Peripheral (significant rod input)	Central
Spatial resolution	Low	High
Contrast sensitivity	Asymptotic at low (10%) contrast	Requires mid-to-high contrast
Spatial frame of reference	Egocentric (absolute body coordinates)	Allocentric (relative object space)
Temporal resolution	High	Low
Primary control mode[a]	Closed-loop	Open-loop
Memory requirements[b]	Low	Moderate-high

[a] See Donges (1978).
[b] See Norman (2002).

the focal (ventral) stream, compared to the ambient system, may be characterized as being: relatively insensitive to high-temporal-frequency stimulus modulations, insensitive to low-spatial-frequency/low-contrast information, capable of resolving high-spatial-frequency stimuli (i.e., fine spatial detail), capable of fine wavelength (color) discrimination, and limited primarily to information delivered to the macular (central) region of the retina (Livingstone and Hubel, 1988; Milner and Goodale, 1996).

2.2.3 A Two-Level Model of Driver Steering

Building upon previous work aimed at constructing a control theory based model of vehicular guidance (see McRuer, Allen, Weir, and Klein, 1977), Edmund Donges (1978) developed and successfully tested his *two-level model of driver steering*. Donges' model has been highly influential in shaping the way the field of human factors psychology has subsequently conceptualized steering behavior. This model has direct parallels to the ambient–focal theoretical framework. Using Donges' own words, the two-process model can be succinctly described as:

> The steering task can be divided into two levels: (1) the guidance level involving the perception of the instantaneous and future course of the forcing function provided by the forward view of the road, and the response to it in an anticipatory open-loop control mode; and, (2) the stabilization level whereby any occurring deviations from the forcing function are compensated for in a closed-loop control mode. (1978, p. 691)

Expressed in terms of the ambient–focal heuristic, Donges' guidance level process is highly reliant upon the focal mode of processing. That is, foveal vision is used to garner information from the "far" road ahead and the driver uses this information to anticipate and prepare for future alterations in the course of the road. In addition to the need for such anticipatory interaction with the visual environment, the driver also depends upon visual information regarding current (i.e., instantaneous) deviations between the vehicle's actual path and its desired path. This later visual requirement, represented by the stabilization level, requires information from the "near" road ahead and, hence, is primarily dependent upon peripheral vision and the ambient mode of visual processing. Other aspects of the two-process model of driver steering map smoothly onto the ambient–focal dichotomy. For example, the foveal/anticipatory process periodically samples the far road ahead in an open-loop fashion and, hence, must be heavily dependent upon higher-level cognitive resources such as the strategic allocation of attention and memory capacity. These characteristics match those of the focal/ventral processing stream (see Norman, 2002). Thus, Donges' two levels (or processes) underlying visually guided steering behavior can be thought of as consisting of an *ambient/near mechanism* that uses peripheral vision to track and null instantaneous errors in lane position and a *focal/far mechanism* that uses central vision and higher-level visual cognition to anticipate (predict) the changing path ahead and to adequately prepare for such changes.

2.2.4 Diagnostic Signature of Ambient versus Focal Mediators of Steering Behavior

Perhaps the most well-known evidence supporting the existence of separate ambient/near and focal/far visual processes as mediators of visually guided steering behavior can be found in the work of Land and Horwood (1995, 1998). Participants in this simulator-based study were required to drive along a narrow and (extremely) winding virtual roadway while lane position performance was recorded. On experimental trials, the view was restricted to narrow horizontal samples of the road ahead (full horizontal extent with 1° vertical height). The relative position of this narrow sample of the road ahead was varied across trials from 1° to 9° below the horizon. At very low speed (i.e., 28 mph), optimal steering performance was achieved when the available visual information was positioned 7°–8° below the horizon (i.e., the very near road ahead). However, at higher speed (i.e., 44 mph), drivers were unable to achieve criterion (baseline) levels of steering stability when limited to a single narrow cross section of the road ahead (no matter where it was positioned). Instead, normal steering performance was maintained only when drivers were permitted to view a second 1° tall horizontal cross section such that the two visible regions of the road ahead sampled the lower (nearest) and upper (farthest) segments of the simulated road scene. Land and Horwood's partial visual occlusion paradigm demonstrated that both near and far visual information are needed to achieve normal levels of steering performance. This finding is highly consistent with the two modes of vision construct; namely, that parallel ambient/near and focal/far visual mechanisms combine to mediate vehicular guidance performance.

Over the past decade, a number of other investigators have used techniques that are somewhat analogous to Land and Horwood's (1995, 1998) partial occlusion technique to provide more direct assessments of both the existence and the dissociation of ambient versus focal contributions to vehicular guidance. The approach used in all of these studies is based upon the logic of systematically degrading a dimension of information in the visual environment that is thought to support either ambient or focal processes, and then observing which dimensions of driving-related performance change across the experimental manipulation (versus which dimensions of performance remain invariant). For example, by systematically decreasing the relative amount of high-spatial-frequency information available to the driver (by using progressively increasing levels of stimulus blur), one would expect driving behaviors related to focal visual mechanisms to become markedly degraded; while those related to ambient visual mechanisms would be expected to show little or no change across the experimental manipulation. Similarly, if one systematically decreased the peripheral field of view available to the driver, one would expect driving performance measures related to ambient visual mechanisms to become markedly degraded while those mediated by focal mechanisms would be expected—in many cases—to demonstrate little or no decline. Such dissociations between performance indices across theoretically significant categories of visual stimulus manipulation represent *diagnostic signatures* supporting the existence of parallel ambient and focal system mediators of driving-related behaviors. Recent studies providing data that can be used to generate such diagnostic signatures are reviewed in the pages that follow. Taken together, these studies provide considerable support for the working hypothesis that the ambient–focal heuristic represents both a valid and potentially powerful tool for improving our understanding of driving behavior.

2.3 EMPIRICAL EVIDENCE FOR AMBIENT–FOCAL MECHANISMS OF STEERING

2.3.1 Experimental Reductions of Visual Acuity

According to the ambient–focal framework, the relative contributions of focal visual processes to driving performance should be markedly reduced when high-spatial-frequency information in the driving scene is attenuated via poor acuity or optical blur. However, the efficiency of ambient visual processes should remain invariant under optical blur because of their insensitivity to high-spatial-frequency information. Higgins, Wood, and Tait (1998) examined the effects of experimental reductions in central visual acuity upon performance while driving around a 5.1 km closed-course road circuit characterized by complex horizontal geometry as well as a slalom course constructed from closely spaced traffic cones. Twenty-four young drivers (mean age = 23.1 years) drove while wearing modified swimming goggles equipped with binocular convex lenses of varying power. Increasing the power of these lenses resulted in decreasing the central acuity of the participants due to blurring of the retinal image. Lens powers were selected to yield functional acuity levels of 1, 2, 5, and 10 minutes of arc (i.e., 20/20, 20/40, 20/100, and 20/200 equivalent Snellen acuity, respectively). Among the driving performance measures recorded in this study,

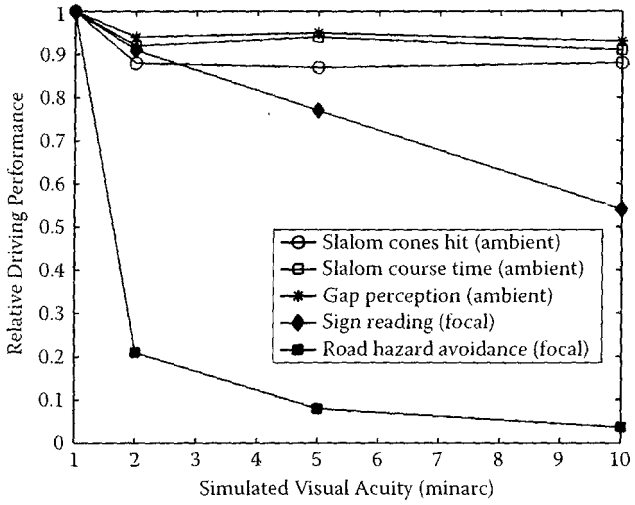

FIGURE 2.1 Relative performance upon five driving subtasks as a function of experimental reductions in central visual acuity. AMBIENT functions are largely unaffected by dramatic reductions in visual acuity, whereas FOCAL functions appear quite sensitive to variations in available visual acuity. (Data source: Higgins, Wood, and Tait, 1998.)

five are considered here because they appear to map well to the presumed ambient–focal dichotomization of visual function. Performance on each of these dependent variables has been normalized to a common relative scale and graphically presented in Figure 2.1 for comparison.

Reference to Figure 2.1 reveals several interesting outcomes regarding the effects of manipulating visual acuity. The first thing to note is that three of the five dependent measures remained virtually invariant as visual acuity was reduced. That is: (1) the number of cones hit while traversing a slalom course delimited by traffic cones (Slalom Cones Hit), (2) the time required to traverse the tight curves of the slalom course (Slalom Course Time), and (3) the ability to judge whether the space between traffic cones was wide enough to permit one's vehicle to pass (Gap Perception) did not significantly decline as simulated visual acuity was reduced from 20/20 (normal vision) to 20/200 (i.e., legally blind in the United States). The fact that these three measures of performance remained essentially invariant across large reductions in the availability of high-spatial-frequency information strongly suggests that they are dependent upon ambient/near visual processes rather than focal/far mechanisms. Yet, two other performance measures demonstrate just the opposite effect. Sign Reading and Road Hazard Avoidance were both found to decline precipitously as visual acuity was degraded. Since these later performance categories unambiguously depend upon the focal mode of visual processing, such effects were clearly anticipated. The dissociation of these two groups of performance functions (labeled AMBIENT and FOCAL in Figure 2.1) across experimental reductions in visual acuity represent the diagnostic signature consistent with the expectations of the ambient–focal heuristic.

That is, evidence that driving behavior is mediated by separate ambient and focal visual streams.

Although the Higgins et al. (1998) investigation can be characterized as having high face validity (i.e., real drivers in a real vehicle), the indices of driving performance collected in this study did not include traditional continuous measures of visually guided steering performance such as variability of lane position or time-to-line crossing. This makes it difficult to integrate their findings with the general scientific literature on visually guided steering behavior. Fortunately, a recent simulator-based study has replicated the effects of the experimental degradation of acuity upon driving performance while extending the results to the domain of continuous measures of steering efficiency. Brooks, Tyrrell, and Frank (2005) used a high-fidelity, fixed-base driving simulator (DriveSafety, Inc.) to investigate the effects of experimentally induced reductions in visual acuity upon various indices of steering performance in a sample of 10 young adults (mean age = 21.2 years). Again, acuity was manipulated through the use of convex lenses that varied in optical power from 0 to 10 diopters (yielding average observed acuities ranging from 1 to 32 minutes of arc (20/20 to 20/647 Snellen acuity, respectively)).

Remarkably, two measures of continuous steering performance remained almost unchanged across this wide range of simulated acuity. The percent time spent entirely within the lane boundaries (mean = 91%; range = 95%–88%) and the standard deviation of lane position (mean = 0.23 m; range = 0.22–0.25 m) remained virtually unchanged while experimental acuity varied from normal levels to well below the criterion for being classified as legally blind. These results reinforce the interpretation that *time-in-lane* and *standard deviations of lane position* are both indices of performance that reflect the level of functioning of the ambient visual system (which relies upon low-spatial-frequency input that is relatively immune to the deleterious effects of blur). These results were also consistent with an earlier report by Owens and Tyrrell (1999) who found that mean lane position error remained unchanged across large reductions in experimental visual acuity. Yet, it is interesting to note that Brooks et al. (2005) also measured two other continuous indices of steering performance that were not robust with respect to the experimental degradation of visual acuity. Both mean *lateral speed* and the *number of lane excursions* (i.e., edge line crossings) demonstrated sizable declines in performance with reductions in experimental visual acuity. This pattern of results suggests that these latter two indices of performance may reflect constraints imposed by focal/far visual processes, while the former indices reflect unconstrained ambient visual processing across the blur manipulation (see Figure 2.2). The classification of lateral speed and lane excursion performance as being mediated by focal/far visual processes is not immediately obvious and cannot be predicted in an *a priori* fashion given the current state of development of the ambient–focal framework. One possible reason for why these two indices became degraded under blur could be as follows: As the level of blur increased, drivers became less able to gather information about approaching curves that would allow them to anticipate large changes in vehicle heading (clearly a task requiring focal/far processes). Entry into such unanticipated curves might thereby be expected to be accompanied by edge line crossings and sudden compensatory increases in lateral speed to restore satisfactory lane position. Such behavior would,

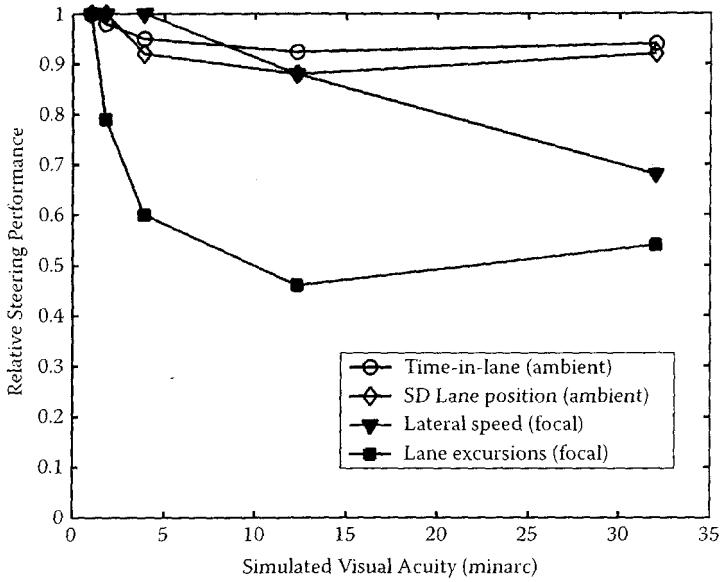

FIGURE 2.2 Relative performance upon four driving subtasks as a function of experimental manipulation of visual acuity levels. Note that two performance indices are invariant across acuity levels (demonstrating the AMBIENT signature), while two other indices decline markedly (demonstrating the FOCAL signature). (Data source: Brooks, Tyrrell, and Frank, 2005.)

in turn, be expected to yield increases in mean lateral speed and the number of lane excursions as the level of visual blur was increased. Indeed, such behavior has been explicitly noted in a related study where visual access to the road ahead was curtailed using an altogether different approach to manipulating preview distance (see COST 331, 1999).

In summary, studies manipulating the level of visual acuity via blur have yielded empirical signatures that strongly support the validity of the ambient–focal framework for understanding vehicular guidance. In addition, these studies have also demonstrated that such signatures can be quite diagnostic in terms of classifying how various dependent measures appear to map onto the ambient–focal dichotomy of visual function in a given experimental scenario.

2.3.2 Experimental Reductions of Roadway Luminance

Although the illumination provided by the sky varies widely between dawn and dusk, the luminance of objects in the daytime driving scene remains well within the eye's photopic range of luminance adaptation (Wyszecki and Stiles, 1982). As a consequence of the eye's ability to quickly adapt to variations in light level within the photopic regime, the amount of light reaching the driver's eyes rarely represents a limiting factor upon vehicular guidance during daytime driving. However, as

night begins and environmental light levels fall below the threshold of *civil twilight** numerous visual functions begin to become degraded. Vehicle headlamps and overhead lighting assist the driver at night. Yet, even with the augmentations provided by these artificial sources of light, the luminance of the typical roadway environment is too low to adequately maintain photopic levels of light adaptation (Olson and Aoki, 1989; Eloholma, Ketomäki, and Halonen, 2004). As a result, the visual adaptation level of the typical nighttime driver can be said to be in the *mesopic* range—a poorly understood middle ground of vision in which neither cone (photopic) nor rod (scotopic) visual functions perform optimally.

The vast majority of the scientific literature on human vision has been conducted under either photopic or scotopic adaptation conditions. It is, therefore, often quite difficult to generalize results from classical laboratory studies to the situation facing the driver at night. This makes the ambient–focal heuristic especially useful in the domain of nighttime driving. Accordingly, driving functions thought to be mediated by ambient visual processes—such as certain aspects of vehicular guidance—should remain robust as luminance is reduced from photopic to near-scotopic levels (i.e., across the full range of mesopic vision). Driving processes thought to be mediated by focal visual processes—such as sign and hazard recognition at a distance—should become increasingly degraded at such low luminance levels. Several recent studies of driving performance have yielded results consistent with this view.

Owens and Tyrrell (1999) used a low-resolution, part-task driving simulation environment to investigate the effects of reductions in roadway luminance upon steering behavior. The delineators marking the edges of the simulated roadway were presented at four different luminance levels: 0.003, 0.03, 1, and 30 cd/m^2. The lowest luminance (0.003 cd/m^2) represented vision in the scotopic regime while the highest luminance (30 cd/m^2) was selected to represent the photopic adaptation state. The remaining two levels were selected to simulate low (0.03 cd/m^2) and high (1 cd/m^2) reflectance objects observed at civil twilight (representing the low and high ends of the mesopic luminance regime). Consistent with the predictions of the ambient–focal heuristic, Owens and Tyrrell found that a continuous measure of steering performance (lane position error) was unchanged as luminance conditions were varied from photopic to low mesopic levels. Only in the scotopic condition was steering performance significantly reduced relative to photopic viewing conditions. Similar findings have been reported by Brooks et al. (2005) using a more sophisticated simulation platform and a related measure of steering performance (percent time in lane). That is, both studies revealed that steering performance—as indexed by lane position—was quite robust across the full range of mesopic luminance. Again, this relative invariance of performance across experimental degradation of the visual environment appears to represent the hallmark signature of the ambient/near visual mechanism (see Figure 2.3).

* Since the days of antiquity, astronomers have observed that skylight is sufficient to support most normal tasks until the end of *civil twilight*—the point at which the sun falls more than 6 degrees below the horizon. Typical roadway illumination provided by the sky at this time is approximately 3 lux at northern latitudes in the United States.

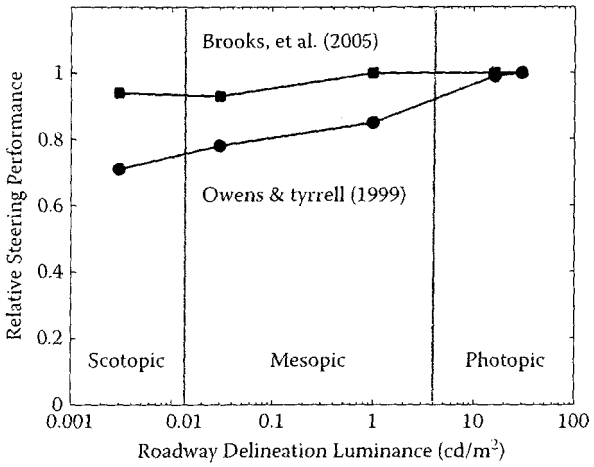

FIGURE 2.3 The robust nature of visually guided steering performance across the scotopic through photopic luminance regimes represents the hallmark signature of a process mediated by the ambient visual system.

2.3.3 Experimental Restrictions of Driver's Field of View

According to the ambient–focal framework, the ambient visual system's contributions to driving performance should become degraded as the field of view is restricted beyond some critical level.

Wood and Troutbeck (1992, 1994) conducted a series of studies which, when combined together, permit a parametric examination of the effects of reductions in the field of view upon various aspects of driving performance. Specially designed goggles were used to restrict the driver's field of view to one of four levels: 20, 40, 90, or 150° (monocular baseline). Performance data were collected while drivers negotiated a slalom course constructed of tightly packed traffic cones and while drivers completed several circuits around a 5.1 km closed course characterized by complex horizontal geometry (see p. 292 of Wood and Troutbeck, 1992, for a map of the Mount Cotton driver training course used in these investigations). Select performance data from both studies have been normalized to foster global comparisons. The effects of reductions in the field of view upon these measures of driving performance are depicted in Figure 2.4.

Two of the performance curves depicted in Figure 2.4 represent indices of vehicular guidance: Lanekeeping and Slalom Cones Hit. Lanekeeping performance, as defined in these studies, is a composite index combining subjective rating scale data and mean lane position data sampled at 45 discrete locations along the test track. The Slalom Cones Hit index was derived from the relative number of traffic cones touched or knocked down while drivers negotiated a slalom course consisting of several very tight curves (Wood and Troutbeck, 1994). Performance on these guidance functions demonstrated little or no decline as available field of view was reduced from 150 to 90 deg. However, remarkable decrements in these indices of vehicular guidance behavior were clearly evident when the field of view was reduced below 40

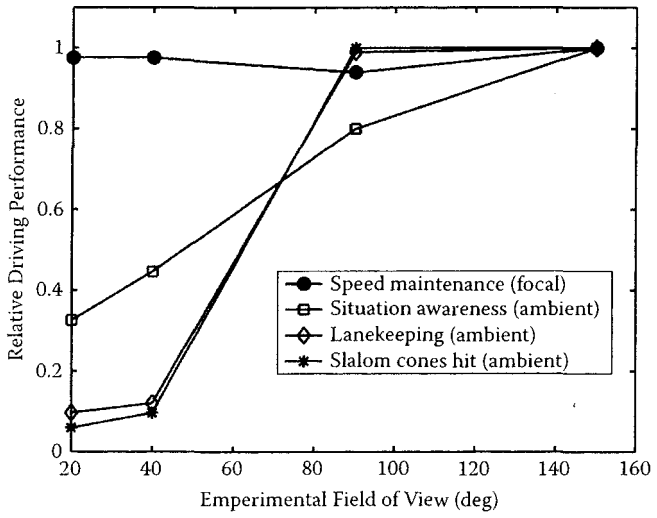

FIGURE 2.4 The effects of systematic restrictions in the field of view upon several measures of driving performance. Note that three of the performance measures demonstrate marked declines as the field of view is diminished. Such changes in performance would be expected for driving skills mediated by the ambient visual system. The surprising invariance of the Speed Maintenance data across changes in the field of view matches the signature of a focal visual process. (Data source: Wood and Troutbeck, 1992, 1994.)

deg. The shapes of these performance functions across experimental variations in the available field of view are consistent with the interpretation that both Lanekeeping and Slalom Cones Hit represented indices of guidance behavior that are mediated by ambient/near visual mechanisms. At least one other performance measure collected by Wood and Troutbeck (1994) also demonstrated a signature that was diagnostic with respect to the ambient visual system. Situation Awareness, representing the relative number of traffic signs and roadside pedestrians that were detected, also declined significantly as the driver's field of view was diminished. Finally, the time required to traverse the closed-course driving circuit (Speed Maintenance) was demonstrated to have been invariant across the experimental manipulation of the driver's field of view. This suggests that visual input into the regulation of driving speed may have involved focal rather than ambient visual mechanisms. This finding is significant because it tends to discount the role of "optic flow" in the far periphery with regard to the regulation of vehicle speed (a function often assigned to the domain of the ambient system; see Riemersma, 1987).

Brooks et al. (2005), whose work was described in some detail earlier, also used their high-fidelity driving simulator to assess the effects of restricted field of view upon vehicular guidance behavior. Young drivers (mean age = 18.5 years) were tested under the following field of view conditions: 1.7, 3.4, 11, 23, and 46 deg. Both monocular and binocular full field (150 deg) baseline conditions were also observed for all participants. The experimental field of view restrictions were implemented by mounting small aluminum cylinders in eyeglass frames and positioning them

just anterior to the pupil of the left eye. Data from four measures of vehicle guidance were collected. All four indices of vehicle guidance performance declined significantly as the field of view was restricted. Like the data of Wood and Troutbeck (1992, 1994), the quality of vehicle guidance appeared to decline when the driver's visual field fell below 40 deg. These investigators failed to demonstrate a pattern of dissociation between the performance variables that was consistent with the ambient–focal framework. However, the interpretation of these results is complicated by the fact that their field of view manipulation was limited to monocular viewing from the nondominant eye in most participants. This work needs to be repeated under binocular viewing conditions.

2.3.4 Experimental Reductions of Roadway Preview Distance/Time

In 1999, a comprehensive study of the visual needs of drivers was completed under a European Cooperation in the Field of Scientific and Technical Research initiative (hereafter referred to as the COST 331 study). One of the goals of the COST 331 study was to set minimum guidelines for the retroreflectivity of pavement marking in support of nighttime vehicular guidance. In order to establish this minimum requirement, the investigative team first had to answer the question: How far down the roadway do edge lines need to be visible to support optimal steering behavior? The primary method used to address this question was based upon a unique driving simulation protocol conducted at the Swedish Road and Transport Research Institute (VTI). Twelve young (25–35 years old) and 12 middle-aged (55–65 years old) participants drove along alternating straight and curved segments of a simulated roadway at a fixed speed of 90 km/h while the visibility distance of the road ahead was systematically manipulated across five levels: 20, 30, 45, 67, and 100 m, respectfully. Figure 2.5 depicts the appearance of the simulated roadway at several different preview distances. Results indicated that the *standard deviation of lane position* was elevated (approximately 0.4 m) at the shortest preview distance (20 m). However, asymptotic performance (approximately 0.23 m) was achieved at preview distances between 30 and 45 m. Providing the driver with additional preview distance was not accompanied by improvements in steering performance. Converting this result to a format that can be easily generalized across various driving speeds (i.e., preview time), these results indicate that asymptotic steering performance is achieved once the driver is provided with 2 seconds of preview time.

These findings from the COST 331 study are especially significant when considered within the framework of the ambient–focal dichotomy. Lateral lane position variability reached minimum levels (optimal performance) with just 2 seconds of roadway preview time. Yet, most investigations of the minimum visual requirements for roadway delineation (including COST 331) estimate that much longer preview times are required for safe and efficient operation of a motor vehicle. For example, Zwahlen and Schnell (2000) estimate a minimum preview time requirement of 3.65 seconds, whereas other investigations conclude that a minimum preview time of 5 seconds is necessary (Weir and McRuer, 1968; Godthelp and Riemersma, 1982; CIE, 1992). This pattern of findings suggests that the point at which lateral road position variability performance becomes asymptotic marks the transition point at which

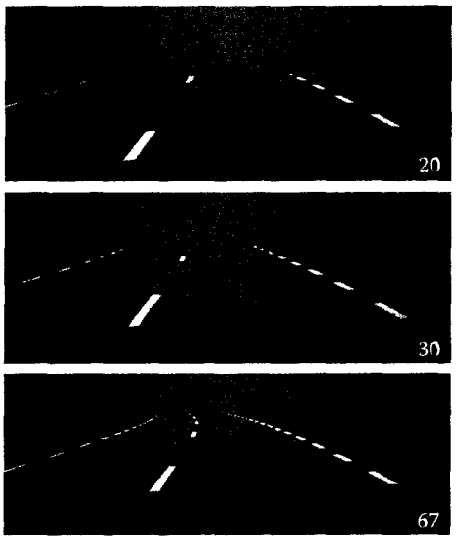

FIGURE 2.5 Examples of three different simulated driving preview distances. Edge lines are visible out to 20, 30, and 67 m, respectively. (Source: COST 331, 1999.)

ambient/near visual processes give way to focal/far visual processes. The ability to delineate the transition point between the near and far visual environments may represent an important advancement for the application of the ambient–focal framework in the service of improving our understanding of visually guided driving behavior.

2.4 HEURISTIC VALUE OF THE AMBIENT–FOCAL FRAMEWORK

The investigations reviewed in the previous section represent a select subset of the available studies on vehicle guidance. They were chosen for inclusion based upon one primary criterion: their ability to link the ambient–focal dichotomization of the visual system to the study of visually guided driving behavior. Two experimental protocols appear to have been particularly effective in demonstrating a dissociation between ambient and focal visual mediators of driving performance. Progressive blurring of the visual scene has been shown to systematically degrade focal mode contributions to driving performance while sparing ambient mode contributions. Progressive reductions in the driver's field of view have been shown to degrade various aspects of driving performance that can be attributed to the ambient mode of visual processing—although perhaps not as unambiguously as the dissociations revealed using the progressive blurring protocol. Additional research is needed to better understand the changes in visual dynamics resulting as a consequence of manipulations of the driver's field of view. Simultaneous records of eye movement behavior during such protocols could contribute much to our understanding of these dynamics.

The functional distinctions between the ambient and focal modes of vision outlined in Table 2.1 suggest several other approaches that could be used to experimentally isolate ambient versus focal contributions to driving-related behavior.

For example, given the strong dependence of ambient vision upon magnocellular input, reductions of display luminance contrast to levels approaching 10% would be expected to maintain the efficiency of ambient mechanisms while dramatically reducing the effectiveness of focal (primarily parvocellular) visual mechanisms. Such a manipulation could be easily instantiated in a driving simulator environment. Yet another approach could be used to attenuate ambient mode contributions in the service of partially isolating focal mode mechanisms of visually guided behavior. That is, a driving simulator could be used to render the visual environment at near-isoluminant conditions (i.e., color contrast with little or no simultaneous luminance contrast). Since the magnocellular inputs making up the ambient stream are "color blind," such an isoluminant stimulus configuration would bypass ambient vision, and, as a consequence, might yield important new insights regarding the differential contributions of focal mechanisms of driving performance.

Another, less speculative approach focuses upon exploring the ambient–focal dichotomy by systematically restricting visual information to the "near" versus "far" domains of vision, respectively. As discussed within the context of the COST 331 (1999) study, this could be accomplished by progressively increasing the preview distance available to the driver until asymptotic levels of lane-keeping behavior were achieved (i.e., minimum standard deviation of lane position). Within the context of the ambient–focal theoretical framework, this point (at which additional preview distance no longer yielded improvements in lane keeping) would mark the end of the "near" range of the visual space subsumed by ambient visual mechanisms. Thus, by restricting available preview to include only the visual world up to this boundary point one could isolate ambient/near visual mechanisms. Similarly, by restricting visual preview to the visual world only beyond this boundary point one could isolate focal/far visual mechanisms. Such manipulations could be accomplished in a driving simulator as well as in a real vehicle on a test track using a very simple visual occlusion technique (see Riemersma, 1987, for an example). It would be most informative to discover which, if any, driving performance indices remained invariant under the "far preview only" condition. Such invariance would be indicative of a performance measure that was sensitive to focal/far visual processes. Myers (2002) has proposed that *time-to-line crossing* (see Van Winsum and Godthelp, 1996) represents a likely candidate for such a diagnostic measure of focal/far visual processing. If experimentally verified, this would allow one to evaluate the ability of a roadway delineation system to support focal/far visual requirements based upon time-to-line crossing data while evaluating its ability to support ambient/near visual requirements based upon simultaneous measures of the standard deviation of road position (relative to their asymptotic levels).

Finally, there is evidence that the ambient–focal theoretical framework may provide a basis for investigating driving behavior well beyond the realm of mere vehicular guidance. For example, this approach holds much promise for improving our understanding of age-related driving problems. Normal adult aging is accompanied by systematic and deleterious changes in the visual system (see Schieber, 1992, 2006). There is a growing body of evidence that ambient visual functions such as low-spatial-frequency motion perception and the useful field of view are especially susceptible to age-related decline (Kline and Schieber, 1981; Owsley et

al., 1998; Schieber, 2006). In addition, there is evidence that age-related deterioration of ambient visual information processing may mediate the increased frequency of "looked but didn't see" crashes among older drivers, especially at intersections (Schieber, 1994, 2000). Perhaps the most direct evidence for this *ambient insufficiency hypothesis* of age-related visual difficulties with driving has been presented by Owens and Tyrrell (1999) who reported that steering performance in older adults was not as resistant to systematic reductions in roadway luminance as their young counterparts. Consistent with this interpretation, Wood (2002) has demonstrated that global motion sensitivity and the ability to rapidly detect and localize targets in the peripheral field were strong predictors of age-related decrements in closed-course driving performance. Additional work is needed to more rigorously assess the ambient insufficiency hypothesis. The techniques described hold great potential for more in-depth evaluation of ambient mode processing efficiency among older drivers.

2.5 CONCLUSIONS: VISUAL REQUIREMENTS OF VEHICULAR GUIDANCE

The studies examined to this point have yielded some noteworthy conclusions about the nature of the visual information required to successfully steer an automobile. Vehicular guidance was found to be remarkably robust in the face of great reductions in available high-spatial-frequency information that accompanies experimental degradations in visual acuity via blur. Drivers with a simulated visual acuity level of 20/200 (i.e., legally blind) demonstrated no systematic reductions in their ability to maintain lane position in straight road driving (ambient/near vision) but did appear to demonstrate some deficiencies in terms of preparatory vehicular positioning in anticipation of sharp curves approaching in the distance (focal/far vision). Similarly, the ability to maintain lane position was found to be quite robust across marked reductions in roadway luminance—becoming significantly degraded only when luminance was reduced to levels approaching those provided by mere moonlight (i.e., the scotopic state of light adaptation). A broad range of driving-related skills, including those related to lane-keeping performance, were found to become significantly degraded when the driver's field of view was experimentally reduced to levels smaller than 40°. Remarkably, speed maintenance was shown to be invariant across even the most severe reductions in the field of view—a finding that is difficult to reconcile with optic flow accounts of speed maintenance.

In summary, it can be concluded that successful vehicular guidance is reliably maintained in the absence of high-spatial-frequency information (20/200 acuity), throughout the full range of mesopic roadway luminance levels (1 cd/m^2 and above), and with a minimum forward field of view (approximately 40 degrees). These are the minimum requirements necessary to achieve nominal levels of steering performance. However, it should be obvious that successful driving involves much more than the simple ability to maintain a vehicle's position on the road. Factors such as sign legibility, hazard detection and anticipation, situation awareness, and many additional vision-based behavioral skills are required to support safe and effective driving in a real-world environment. The ambient–focal heuristic, together with its

associated family of protocols for systematically manipulating qualitatively distinct categories of visual information, appears to hold significant potential for exploring and better understanding the visual inputs necessary to support these higher-order functions. It is the hope of the authors that this review of the ambient–focal framework will help foster such developments.

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