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The view from the road: The contribution of on-road glance-monitoring technologies to understanding driver behavior

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ABSTRACT

Using glance-monitoring technologies for on-road studies is an excellent way to investigate driver behaviors in an ecologically valid setting. Recent advances in glance-monitoring technologies have made it possible to conduct on-road studies of drivers' glance behavior that heretofore were simply not possible. Yet it is not always easy to determine which glance-monitoring technology to use for a particular application. Here, we first identify the generic capabilities of the various glance-monitoring technologies. We then describe how particular glance-monitoring technologies have been used in the field to (a) identify the skill deficiencies of novice and older drivers, (b) evaluate the effectiveness of training programs that are designed to reduce deficits in these skills, and (c) address interface issues both inside (e.g., collision warning systems) and outside (e.g., yield markings) the vehicle. The limitations and advantages of on-road eye-tracking and the associated glance-monitoring technologies are identified throughout. A comparison, where possible, is made between the results of on-road eye-tracking studies of drivers' behaviors and the results of those studies conducted in the laboratory. Overall, the use of appropriate on-road glance-monitoring technologies has greatly enhanced our theoretical understanding of why drivers behave the way they do, and this knowledge has paved the way for significant improvements in road user safety.

1. Introduction

When a crash occurs, it is relatively easy to diagnose whether a vehicle malfunction was the primary cause of the crash. However, it is much more difficult to determine whether there was a driver failure, and if so, precisely diagnose what the failure was. Only recently has it become possible to diagnose driver errors that actually occur on the open road and then establish, again on the open road, that training programs, new in-vehicle technologies, or advanced signs, signals and pavement markings can actually remediate and/or prevent these errors.

One part of the problem in diagnosing, remediating, and preventing driver errors that lead to crashes is that measures such as vehicle crash rates are only indirectly related to the latent cognitive processes which are responsible for those errors. Eye-tracking technologies, and more general glance-monitoring technologies, more directly measure these processes. It has been possible to employ such technologies in the laboratory and there is a long history of successful research using this approach (Crundall and Underwood, 2011; Fisher et al., 2011a,b; Shinar, 2008). But until recently, except for the one or two on-road glance-monitoring studies in the early 1970s (e.g., Rockwell, 1972), it has been simply too cumbersome or too expensive to gather eye behaviors on the open road. However, recent advances have made it much easier to collect measures of drivers' eye behaviors on the open road that are more closely linked to latent cognitive processes.

We begin our review by discussing the various glance-monitoring technologies that have been used in on-road studies, their generic capabilities, and issues related to the use of such technologies (Section 2). The review continues with coverage of a range of on-road glance-monitoring studies of driver behaviors, focusing on one category of study in each section: studies that directly

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Table 1
Glances outside the vehicle, as measured by various glance-monitoring technologies. HM = head mounted; VM = vehicle-mounted; ET = eye tracker; SC = scene camera. Scene cameras are pointed at the road ahead/to the sides/to the rear.

	HM eye tracker (HM-ET)	HM eye tracker + HM scene camera (HM-ET–HM-SC)	HM scene camera (HM-SC)	VM face camera (VM-FC)	VM eye tracker (VM-ET)	VM eye tracker + VM scene camera (VM-ET–VM-SC)
Fixation location relative to head	+	+			+	+
Fixation location in real world		+				+
Fixation duration	+	+			+	+
Fixation duration on an object		+				+[3]
Glances to the side		+	+[1]	+[2]		+[3]
Glance durations to side		+	+[1]	+[2]		+[3]
Glance location behind vehicle		+				
Looking at the forward roadway		+	+	+		+
Records only locations at which head/eyes are directed		+	+			+
Records entire scene regardless of where head/eyes are directed						+

[1] Glances to the side (or mirrors) and the duration of these glances are captured only if the driver moves his or her head; what the driver sees is available from the video.
[2] Glances to the side can be captured without the driver having to move his or her head; but what the driver sees is not captured.
[3] Typically the capture is limited to 30° to the side.

identified the behaviors that have been inferred to be the major causes of crashes among younger novice (McKnight and McKnight, 2003) and much older experienced (Clarke et al., 2010) drivers (Sections 3 and 4); studies that evaluated training programs intended to modify the behaviors of younger and older drivers (Section 5); and studies that tested the effects on driver behaviors of changes in the design of the interface between the user and either a system with which the driver interacts inside the vehicle (Section 6) or signs, signals, and pavement markings with which the driver interacts outside the vehicle (Section 7). In each section, we discuss the insights provided by on-road glance-monitoring technologies, the limitations of the particular technologies that were used, and the ways in which these insights differ, if at all, from studies conducted in the lab (e.g., simulator studies, video clips). These insights are sometimes theoretical, sometimes practical, and sometimes both.

2. Monitoring glance behaviors

Some of the most informative measures of cognitive processing associated with driving can be extracted from a record of a driver's eye and head movements using eye-tracking or more general glance-monitoring technologies. The most critical index we focus on is the *glance*, or where the eyes are pointing and for how long. The measurement of *glance location* can be used as a proxy for determining what information a driver is processing. For example, glances can be used to infer whether a driver maintains attention to the forward roadway, as opposed to attending to distractions near the road or within the vehicle (*attention maintenance*). Glances can also be used to infer whether a driver anticipates a particular hazard as measured by whether the driver checks the critical location or locations from which a hazard is likely to emerge (*hazard anticipation*). Significantly, such attention maintenance (Klauer et al., 2006) and hazard anticipation (Horswill and McKenna, 2004) behaviors have been shown to relate directly to crashes and thus are a major focus of this review. Our discussion below, however, does not assume that glance measurements are a perfect index of the information to which the brain is attending. Nevertheless, having acknowledged this, we should mention that there is a large body of research indicating that there is a close relationship between the location of a glance and the information to which an individual is attending in normal visual perception. More specifically, although there is no guarantee that an individual successfully processes what his or her eyes are pointing to, there is little chance in normal perception that much, if anything is processed about locations that are not fixated (e.g., Divekar et al., 2012; Henderson, 1993; Rayner, 2009).

In the context of static visual scene perception research, indices of eye movement behavior such as fixation durations, gazes, gaze durations, and visual pursuit movements are formally defined (Rayner and Pollatsek, 1989). In driving, the analog to gazes is glances. A *glance is* defined as a sequence of fixations or smooth pursuit movements confined to a particular spatial location (e.g., the interior of a vehicle, in which case the coordinate system is driver centered, or a fixed object such as a road sign, in which case the coordinate system is centered in the outside world). *Glance duration* is the length of time that a driver spends looking at a predefined location, which is measured from the moment the driver first fixates a point within the boundaries of the location to the moment the driver first fixates a point outside this predefined boundary (thorough definitions can be found in ISO, 2002a,b; Society of Automotive Engineers, 2001).

The major categories of glance-monitoring technologies include head mounted eye trackers (HM-ET), head mounted combination eye trackers and scene cameras (HM-ET–HM-SC), head mounted scene cameras (HM-SC), and vehicle-mounted face cameras (VM-FC). There are now vehicle-mounted eye trackers (VM-ET) and vehicle-mounted combination eye trackers and scene cameras (VM-ET–VM-SC) that have properties similar, but not identical, to their head mounted versions. The information available from the glance-monitoring technology depends very much on the type of technology that is used (Tables 1 and 2).

The capabilities of these various methods by which glances can be monitored (HM-ET, HM-ET–HM-SC, etc.) will be discussed below. For clarity, first the focus will be on the capability of each technology to analyze glances to locations outside of the vehicle, and then the focus will be on the capability of each technology to analyze glances to locations inside of the vehicle.

When an experiment includes the goal of analyzing glances made to locations outside of the vehicle, as in uninterrupted driving, there are various types of data one may collect from glances. The most basic measurements include collecting information on the range or variability of the eye movements with respect to the head in different environments, or the differences in fixation durations in different conditions. These basic motor measurements are sometimes used to evaluate the costs of cell phone use while driving. For this, a head mounted or vehicle-mounted eye tracker is all that is required (HM-ET, VM-ET). When an experiment requires the analysis of the distribution of glances to general areas, e.g., ahead or to the side, at which a driver is looking, only gross glance location measures are required. In this case a head mounted scene camera (HM-SC) or vehicle-mounted face camera (VM-FC) can adequately complete the task without the expense or complication of