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The sensitivity of different methodologies for characterizing drivers' gaze concentration under increased cognitive demand

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ABSTRACT

An observer's visual scanning behavior tends to narrow during periods of increased cognitive demand. Thus, measures of gaze concentration have become a popular method of gauging cognitive demand, but the consensus on the best method for computing gaze concentration is still evolving. This analysis considers measures of gaze concentration while driving an on-road vehicle, with and without two types of secondary cognitive demand (auditory and visuospatial working memory). We compare the advantages and disadvantages of several different methods for measuring gaze concentration, as well as a direct statistical comparison of their relative sensitivities. We find that several methods produce similar effect sizes, and that these are consistent across task types. Horizontal gaze dispersion, as measured from the standard deviation of horizontal gaze position, attained the largest effect size, indicating that it is the most sensitive to changes in gaze concentration under cognitive demand, while also being one of the simpler metrics to calculate. Our results show that complex eye tracking data sets from applied, ecologically valid situations such as on-road driving can be analyzed effectively with maximal sensitivity and minimal analytical burden to produce a robust measure of a driver's general allocation of attention.

1. Introduction

A diverse body of evidence suggests that cognitive processing is constrained by a variety of capacity limitations. These limitations have been demonstrated across a large number of experimental paradigms, including attentional blink (Raymond, Shapiro, & Arnell, 1992), auditory processing, (Kunar, Carter, Cohen, & Horowitz, 2008; May, Kennedy, Williams, Dunlap, & Brannan, 1990), working memory, (Fougnie & Marois, 2006), and visual search (Zelinsky, Rao, Hayhoe, & Ballard, 1997). When an observer's overall cognitive workload increases, his or her cognition and behavior may undergo compensatory changes that allow one task to be prioritized over another. For example, target processing in rapid serial visual presentation (RSVP) streams favors the first target (Raymond et al., 1992), eye movement patterns "zoom in" as a more detailed visual search is required (Zelinsky et al., 1997), and eye movement patterns contract as the difficulty of a tone counting task increases (May et al., 1990).

Cognitive-behavioral trade-offs under increased workload are also often observed outside the laboratory, particularly in the context of automotive research. The act of driving a motor vehicle, already a demanding task, has only grown more complicated

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in recent years. Tasks undertaken while driving a vehicle have evolved from a set of relatively simple visual and manual demands, such as tuning the radio, to include an array of cognitively demanding activities, such as voice control of complex embedded vehicle systems and smartphone interactions. Visually demanding non-driving activities have a clear impact on a driver's ability to monitor the roadway. These activities can be characterized by measures such as total glance time, maximum glance time, etc. The Alliance of Automobile Manufacturers (2006), International Standards Organization (ISO, 2002) and more recently The National Highway Traffic Safety Administration (2013) provide guidance on the use of these metrics.

Increases in cognitive demand have been shown to impact drivers' allocation of attention to the roadway (Harbluk, Noy, Trbovich, & Eizenman, 2007; Liang & Lee, 2010; Reimer, Mehler, Wang, & Coughlin, 2010; 2012; Victor, Harbluk, & Engström, 2005). As cognitive demands increase, drivers are prone to concentrate their gaze directly in front of the vehicle. This gaze concentration is associated with a diminished ability to detect both peripheral and central targets, and a reduced frequency of glance to mirrors and the speedometer (Hammel, Fisher, & Pradhan, 2002; Harbluk et al., 2007; Liang & Lee, 2010; Nunes & Recarte, 2002; Recarte & Nunes, 2000; 2003; Strayer, Drews, & Johnston, 2003; Victor et al., 2005). These observations are consistent with a loss of situational awareness, inattentional blindness, and situations of ''look-but-fail-to-see'' (Kass, Cole, & Stanny, 2007; Recarte & Nunes, 2003; Reimer, Mehler, Wang, & Coughlin, 2012; Strayer et al., 2003). While various guiding principles have been established to characterize a glance-based assessment of visual demand, little consensus exists on how to most sensitively characterize changes in gaze concentration under added cognitive demand.

1.1. A brief history of gaze metrics

Eye gaze data have been used to characterize changes in cognitive load while driving for a number of years (Harbluk, Noy, & Eizenman, 2002; Sodhi et al., 2002; Victor et al., 2005). One of the more intuitive measures of changes in drivers' gaze under added cognitive demand is percent road center (PRC). PRC is defined as the percentage of fixations that fall within a predefined road center area during a specific period. PRC has been shown to increase with heightened cognitive demand (Engström, Johansson, & Östlund, 2005; Harbluk et al., 2002, 2007; Recarte & Nunes, 2000; Victor et al., 2005). While PRC is conceptually easy to understand, the definition of road center varies considerably across studies. Harbluk et al. (2007) employed a rectangular region 15° wide centered directly in front of the vehicle in the lane of travel. In one study presented in Victor et al. (2005), a rectangular region of 20° was considered. In another set of studies, Victor et al. (2005) defined the road center as a fixed circle with a diameter of 16° centered about the road center point. Extending this methodology further, Ahlstrom, Kircher, and Kircher (2009) considered a circular region, also 16° in diameter, centered on the driver's most frequent gaze angle.

Harbluk et al. (2007) based the computation of PRC on fixations identified from gaze positions. Other implementations of PRC (Ahlstrom et al., 2009; Victor et al., 2005) have used raw gaze points, a gaze trail recorded from an eye tracking system that is not clustered into fixations and saccades. In a comparison between these approaches, Ahlstrom et al. (2009) showed a strong correlation between fixation-based PRC and raw gaze-based PRC (mean $R = 0.95$).

The standard deviation of gaze points—whether computed from the observer's gaze angle or the projection of the gaze trail on a plane in front of the driver—have also been used to characterize changes in gaze behavior with cognitive demand (Reimer, 2009; Reimer et al., 2010, 2012; Sodhi et al., 2002; Victor et al., 2005). Sodhi et al. (2002) assessed the standard deviation of raw gaze points independently for the horizontal and vertical aspects of a driver's scan path. Reimer (2009), 2012) followed this conceptual model of independent analysis of the horizontal and vertical gaze components, while Victor et al. (2005) combined the vertical and horizontal components of gaze angle into a single gaze vector.

This paper examines the sensitivity of different approaches to characterizing changes in driver gaze in a field driving dataset encompassing periods of single task driving and driving under periods of moderate cognitive demand from two secondary tasks. The two approaches for computing PRC (fixation-based and unfiltered gaze-based), two methods of characterizing road center (rectangular world-based and circular gaze-based), and three approaches for assessing the standard deviation of gaze points (combined vertical and horizontal position, and the independent vertical and horizontal positions) are compared. Direct quantitative comparisons between the methods are presented to characterize their relative sensitivities.

2. Methods

2.1. Participants

This study uses data collected from the first session of a larger investigation of the driving behavior of older drivers (Dobres et al., 2013). The first session comprises baseline data for each subject, before any experimental interventions pertaining to the larger study were performed. A total of 38 subjects (21 males) between the ages of 60 and 75 took part in the study. Participants were required to be active, experienced drivers with a valid driver's license for at least the past 3 years. Participants were required to meet additional criteria: driving on average more than 3 times per week; having a driving record free of reported accidents for the past year; being in good health for their age; feeling comfortable driving a full-sized sedan; being free from major medical conditions or psychiatric disorders; and not currently taking a hypertensive prophylactic or somnolent drugs. Individuals who required corrective eyeglasses for normal driving were excluded in order to obtain robust eye tracking data (contact lenses were permitted). Recruitment was carried out in the greater Boston area. The study was approved by MIT's institutional review board.