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Examining drivers' eye glance patterns during distracted driving: Insights from scanning randomness and glance transition matrix

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ABSTRACT

Problem: Visual attention to the driving environment is of great importance for road safety. Eye glance behavior has been used as an indicator of distracted driving. This study examined and quantified drivers' glance patterns and features during distracted driving. *Method:* Data from an existing naturalistic driving study were used. Entropy rate was calculated and used to assess the randomness associated with drivers' scanning patterns. A glance-transition proportion matrix was defined to quantity visual search patterns transitioning among four main eye glance locations while driving (i.e., forward on-road, phone, mirrors and others). All measurements were calculated within a 5 s time window under both cell phone and non-cell phone use conditions. *Results:* Results of the glance data analyses showed different patterns between distracted and non-distracted driving, featured by a higher entropy rate value and highly biased attention transferring between forward and phone locations during distracted driving. Drivers in general had higher number of glance transitions, and their on-road glance duration was significantly shorter during distracted driving when compared to non-distracted driving. *Discussion:* Results suggest that drivers have a higher scanning randomness/disorder level and shift their main attention from surrounding areas towards phone area when engaging in visual-manual tasks. *Practical applications:* Drivers' visual search patterns during visual-manual distraction with a high scanning randomness and a high proportion of eye glance transitions towards the location of the phone provide insight into driver distraction detection. This will help to inform the design of in-vehicle human-machine interface/systems.

1. Problem

Visual attention to the driving environment is of critical importance to safe driving. Drivers need to scan the roads and surrounding areas frequently to maintain awareness of their driving environment. Failure to attend to appropriate locations when driving could cause critical information misdetection, and therefore increase crash risks. Engaging in non-driving related activities often lead to drivers' visual attention away from the road (Green, 1999). Cell phone usage while driving is one of the most popular secondary tasks, and has been frequently reported to increase crash risks and decrease driving performance due to drivers' inattention to the roadway (Bao, Flannagan, Xiong, & Sayer, 2014; Charlton, 2009; Shinar, Tractinsky, & Compton, 2005). According to the National Highway Traffic Safety Administration (NHTSA) data, 3179 people were killed and 431,000 were injured on U.S. roadways that involved distracted driving, which accounts for 10% of all fatalities and 18% of all injuries in 2014 (NHTSA, 2016). Of those, 13% of distraction-affected fatalities and 8% of distraction-affected injuries involved cell phones. Thus, approximately 1.3% of all fatalities and 1.4% of distraction-affected injuries that were reported were associated with cell phone usage as a distraction. Eye glance behavior has been used in many studies as an indicator of distracted driving (Bao et al., 2014; Liang, Lee, & Yekhshatyan, 2012; Victor, 2005). Previous research found that drivers who engaged in visual-manual tasks related to cell phone usage (e.g. dialing or texting) had substantially shorter on-road gaze length when compared to when they were not involved in visual-manual tasks (Bao et al., 2014). Different in-vehicle tasks vary somewhat for mean off-road glance duration, and considerably for the number of glances away from the road and the total glance time required to complete the task (Dingus, Hulse, Antin, & Wierwille, 1989; Wierwille, 1993). A study of in-vehicle information systems indicated that, as the visual task became more difficult, drivers looked at the display for longer periods, and for more varied durations (Victor, Harbluk, & Engström, 2005). The visual requirement (glance length and number of glances) for the use of in-vehicle devices was also used in the item of predicting crash rates, by incorporated with the frequency of in-vehicle device use (Wierwille & Tijerina, 1998). Crash risk increases with longer periods of time that drivers look away from the road (Bao et al., 2014). Off-road glances exceeding 2 s during a safety-critical event doubled the risk of crashes/near-crashes (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). A simulation study, which compared drivers' eye glance behavior between during in-vehicle secondary tasks and during baseline driving when following other vehicles, found that increase

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on-road glances and shorten the entire off-road glances could reduce the likelihood of crash and injury risks (Bärgman, Lisovskaja, Victor, Flannagan, & Dozza, 2015).

Drivers' visual search pattern is also of great importance in understanding how drivers deal with the primary driving task, in-vehicle secondary tasks, and the driving surroundings. Previous experimental driving tests found that experienced or trained drivers showed more extensive scanning on a demanding target section (Chapman, Underwood, & Roberts, 2002; Underwood, Chapman, Bowden, & Crundall, 2002). Visual search is one of the most common sub-tasks carried out with displays. Experiments were conducted to examine how characteristics of in-vehicle tasks impact drivers' visual scanning, and found that task priority had a significant impact on scanning (Horrey, Wickens, & Consalus, 2006). Drivers looked less at the road center area ahead but more often at the in-vehicle display, as the visual task became more difficult (Victor et al., 2005). An on-road experiment conducted to examine the effect of cognitive distraction on visual search pattern found that, drivers spent more time looking centrally ahead and spent less time looking to the areas in the periphery when looking outside of the vehicle; drivers also reduced their visual monitoring of the instruments and mirrors, with some drivers abandoning these tasks entirely (Harbluk, Noy, Trbovich, & Eizenman, 2007). A probability vector and transition proportion matrix has also been introduced and used in eye movement analysis during visual search tasks, and was proved a particularly suitable measure of observer strategies in relation to performance on tasks (Ponsoda, Scott, & Findlay, 1995). However, no studies have been conducted to quantify eye glance patterns during distracted driving.

This study is designed to examine, quantify, and compare drivers' eye glance patterns under cell phone and non-cell phone use conditions. Specifically, the study purposes are two-fold: to investigate drivers' visual scanning randomness and eye glance behavior during cell phone use related to distracted driving; and to quantify the corresponding probabilities between on-road and off-road glance transitions. Glances were assessed for direction and duration, and the glance patterns under non-distracted and distracted conditions were compared within and across drivers. Existing naturalistic driving study data were used to achieve the purposes. Naturalistic driving data has the advantages of providing more natural and detailed vehicle and driving information to examine drivers' eye glance behavior associated with secondary task engagement in real-world settings as compared to typical laboratory tests using driving simulators or test tracks. It was hypothesized that when drivers engage in secondary tasks with a cell phone that they have higher scanning randomness/disorder levels and reallocate their main attention frequently while transitioning from the surrounding environment towards the cell phone.

2. Method

2.1. Data extraction

The data from an existing naturalistic driving study, the Integrated Vehicle-Based Safety System (IVBSS) field operational test (FOT) (Sayer et al., 2011) were used in this study. The IVBSS FOT was designed to build and test an integrated in-vehicle crash warning system for both heavy truck and light vehicles. The integrated crash-warning system used information gathered by inertial, video, and radar sensors, plus a global-positioning-system module and an on-board digital map. Data were collected at frequencies ranging from 10 to 50 Hz. A total of 108 subjects from three age groups (younger, middle-aged, and older) participated in the IVBSS FOT.

A total of 2149 cell phone-related visual/manual (VM) task events (e.g., dialing and texting) were observed from a previous study (Xiong, Bao, Kato, & Sayer, 2015). For this analysis, a set of five-second "distracted event" video clips of drivers engaging in visual-manual tasks were selected and coded to identify drivers' eye glances. Additionally, corresponding baseline five-second clips without distraction were also selected. Criteria were further applied to the data extraction as follows:

- Events contained high-quality data (to exclude events with poor glance determination due to glare or the presence of sunglasses);
- Cell phone-related events were at least 30 s long (to exclude very short visual/manual tasks);
- Driving speed was at least six m/s (to exclude cell phone events that occurred when the car was not moving);
- Vehicle was traveling on known public surface streets or freeways;
- All selected cell phone event clips and their corresponding baseline clips matched on driver, roadway type, traffic density and time of day;
- Each of the drivers had at least three selected distraction events and three matched baseline clips.

As a result, the final dataset that was used in this analysis included 110 event clips and 100 baseline clips from nineteen drivers. The age and gender information of the subjects is summarized in Table 1.

2.2. Variables and data analysis

All the measures in this study were calculated based on 5 s duration for each clip. In the process of coding drivers' eye glance behavior, nine eye-glance locations were defined in this study as forward, phone, left side mirror, rear view mirror, stack, left, right, dash and others (Fig. 1). The number of glances was accumulated once drivers changed the location of eye glance saccades during each selected driving clip. The on-road glance duration was the total time span of drivers looking on the road when driving. In this study, the mean glance duration was also calculated as the mean value of time duration spent on each eye glance location of. Importantly, entropy rate was used as a measure to glance randomness order (Bao & Boyle, 2009). The calculation of entropy rate was defined in Eq. (1).

$$\text{Entropy rate} = \sum_{i=1}^{D} \frac{E/E_{max}}{DT_{x_i}} \tag{1}$$

where E is the information entropy of a discrete random variable x_i, that denotes the fixation location x at scan i and defined as

$$E = -\sum_{i=1}^{D} P_{x_i}\ log_2 P_{x_i} \tag{2}$$

The variable P_{x_i} defines the probability of occurrence of x_i and D is the number of variables in the visual scanning sequence. The maximum entropy, E_{max} is achieved when each x_i has an equal probability of occurring, or at $P_{x_i} = 1/D$. Therefore, $E_{max} = \log_2 D$. The average fixation duration in the visual scanning sequence is denoted as T_{x_i}.

The number of visual scanning areas (i.e., variable x_i) in a consecutive sequence, D, is based on all nine regions, shown in Fig. 1. The shortest fixation of a visual scan area is defined as 0.1 s (1 frame of the video footage). The entropy rate calculation measures the visual scanning randomness with higher values representing greater randomness. Based on the entropy rate calculation, the minimum entropy rate will be zero when there is minimum randomness as defined by repeated samples fixated in only one area. Conversely, if the driver

Table 1
Drivers' information by age and gender.

	Younger	Middle-aged	Older	Total
Male	7	5	1	13
Female	4	1	1	6
Total	11	6	2	19

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