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Modeling visual sampling on in-car displays: The challenge of predicting safety-critical lapses of control ☆

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ABSTRACT

In this article, we study how drivers interact with in-car interfaces, particularly by focusing on understanding driver in-car glance behavior when multitasking while driving. The work focuses on using an in-car touch screen to find a target item from a large number of unordered visual items spread across multiple screens. We first describe a cognitive model that aims to represent a driver's visual sampling strategy when interacting with an in-car display. The proposed strategy assumes that drivers are aware of the passage of time during the search task; they try to adjust their glances at the display to a time limit, after which they switch back to the driving task; and they adjust their time limits based on their performance in the current driving environment. For visual search, the model assumes a random starting point, inhibition of return, and a search strategy that always seeks the nearest uninspected item. We validate the model's predictions with empirical data collected in two driving simulator studies with eye tracking. The results of the empirical study suggest that the visual design of in-car displays can have a significant impact on the probability of distraction. In particular, the results suggest that designers should try to minimize total task durations and the durations of all visual encoding steps required for an in-car task, as well as minimize the distance between visual display elements that are encoded one after the other. The cognitive model helps to explain gaze allocation strategies for performing in-car tasks while driving, and thus helps to quantify the effects of task duration and visual item spacing on safety-critical in-car glance durations.

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1. Introduction

Ubiquitous computing has brought a wealth of information and entertainment to the fingertips of drivers. Although there are clear benefits to the increased availability of services and infotainment on the road, there may be serious drawbacks: in-car visual tasks increase the probability that driver's eyes wander from the road, potentially leading to unsafe situations for the driver and others. Extensive field studies have noted the statistical relationship between in-car glance durations and the probability of safety-critical incidents (see Liang et al., 2012). While the responsibility of safe driving belongs primarily with the driver, those who design and build in-car user interfaces also strive to minimize the potential of visual distraction of these interfaces.

The U.S. National Highway Traffic Safety Administration (2013) recently released testing and verification guidelines for in-vehicle electronic devices. These guidelines propose three criteria for newly developed in-car systems:

1. Individual glance durations: "For at least 21 of the 24 test participants, no more than 15% (rounded up) of the total number of eye glances away from the forward road scene have duration of greater than 2.0 s while performing the testable task one time".
2. Mean glance duration: "For at least 21 of the 24 test participants, the mean duration of all eye glances away from the forward road scene is less than or equal to 2.0 s while performing the testable task one time".
3. Total glance time: "For at least 21 of the 24 test participants, the sum of the durations of each individual participant's eye glances away from the forward road scene is less or equal to 12.0 s while performing the testable task one time".

As a complement to such guidelines, there are various helpful procedures (e.g., SAE-J2365, 2002) and prototyping tools (e.g., Distract-R: Salvucci, 2009) available for designers for analyzing relevant measures of driver distraction and performance, such as in-car task completion times and effects on lateral vehicle control. However, these methods are currently unable to predict arguably the most

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safety-relevant aspect of multitasking while driving, namely in-car glance behavior (NHTSA, 2013; Liang et al., 2012) and to provide guidance in design to create in-car user interfaces that would pass the NHTSA criteria. At least for now, designers and manufacturers must still rely on expensive and time-consuming testing with human drivers on novel in-car user interfaces. A deeper understanding of drivers' visual sampling strategies would go a long way toward more rigorous testing procedures, empirical and otherwise, to better predict and alleviate driver distraction.

In this paper, we study how drivers perform visual sampling on an in-car device interface, specifically when searching through a large number of unordered visual items (e.g., radio stations, music albums and songs, navigational points of interest) spread across multiple screens. Specifically, we study the effects of two possible layouts for its visual items: a *Grid* layout with a constant number of columns and varying number of rows, and a *List* layout with a vertical list of all items. Kujala and Saariluoma (2011) found higher individual in-car glance durations by increasing the number of items per screen as well as increased glance durations for a Grid-style menu layout compared to a list layout.

The results of the current work help in understanding the effects of unordered menu layout on driver glance behavior, and more generally, to elucidate possible gaze allocation strategies used by drivers when interacting with in-car displays. As such, we hope to better understand drivers' visual sampling in general and in the context of recent guidelines and tools like those mentioned above.

We begin by specifying a proposed strategy for visual sampling while driving, along with an instantiation of this strategy as a computational cognitive model developed in the ACT-R cognitive architecture (Anderson et al., 2004). The proposed strategy is based on several key assumptions: (1) each in-car glance begins with the driver fixating a random item on the display; (2) after encoding the current item, the driver transitions to the nearest yet-unattended item (in unordered menus), thus inhibiting return to attended items; (3) drivers monitor the passage of time during performance of the search task; (4) to the best of their ability, drivers try to limit their glances at the display to a reasonable amount of time, after which they switch back to the driving task; (5) drivers adjust their time limits for search based on their performance in the current driving environment. Given this sampling strategy and model, we describe two experiments that provide human data to elucidate these issues and to test the validity of the claims as embodied by the cognitive model.

2. Visual sampling while driving: strategy and model

Visual search construed most broadly is an extremely interesting and challenging problem with many aspects (Wolfe, 2007). In the context of in-vehicle interfaces, visual search can take on a more specific form in three ways. First, visual search is often constrained to a set of similarly sized items with text labels and/or icons; certainly this is not always the case (e.g., search in a navigational map), but is one common case for in-vehicle interfaces. Second, visual search often occurs across multiple screens of items: because an in-vehicle display can typically hold a very limited set of items, scrolling across screens is likely in many search scenarios. Third, the visual search is not continuous, but instead done by brief in-vehicle glances returning vision back to the road in between the glances (i.e., visual sampling). Thus, as mentioned, we focus our efforts on visual sampling in the context of a Grid or List of varying number of items spread across multiple screens.

2.1. Visual-search strategy

We begin by proposing a core strategy for visual search while driving, borrowing a number of ideas from previous models of visual search in non-multitasking contexts. First, we assume that the visual-search task is interleaved with driving in a series of glances to the display (for search) that are interleaved with glances to the roadway (for driving). An *in-car glance* is defined here (following SAE-J2396: SAE, 2000) to begin once the gaze starts to move towards the in-car display, and to end once the gaze has returned to the road scene. Thus, an in-car glance can comprise several fixations on the in-car display.

Each in-car glance begins with the driver fixating a random item on the display. When the driver finishes encoding the current item, we assume, following the model of Halverson and Hornof (2007), that the driver transitions to the nearest yet-unattended item; if there are multiple nearest unattended items, the driver chooses one at random. The limitation of this kind of search model is that it does not probably apply to semantic and alphabetic organizations of items (Bailly et al., 2014). Thus, here we are modeling search behaviors in unordered menus. It also assumes inhibition of return to attended items, which has been found in standard visual-search paradigms (e.g., Klein, 2000; Posner and Cohen, 1984) but has not, to our knowledge, been explored in a similar multitasking context. The central issue here is whether "markers" of attended items (e.g., "FINSTs": Pylyshyn, 1989) persist across multiple glances to a display—or, put another way, whether the items marked as attended will remain marked after an interleaving glance to the roadway and the associated time needed to focus on the driving task.

2.2. Interleaving strategy

The next challenge in our understanding of visual sampling while driving concerns the timing of interleaving between the search and driving tasks. Our understanding of this process generally follows the guidelines of the theory of threaded cognition (Salvucci and Taatgen, 2008), which assumes that each task is associated with a distinct cognitive "thread" and that these threads share cognitive resources in a balanced manner. However, this theory does not dictate one important piece of driver behavior, namely how the driver shares visual resources between the two tasks. For this purpose, we make three important assumptions: (1) that drivers are aware of the passage of time (to the best of their ability) during performance of the search task; (2) that drivers try to limit their glances to a reasonable amount of time, after which they switch back to the primary driving task; and (3) drivers adjust their time limits for search based on aspects of, and their performance in, the current driving environment.

Related to the first two assumptions, Wierwille (1993) found that drivers try to limit in-car glances within the range of 500 – 1600 ms in most real-world driving environments. Related to the third assumption, Wierwille (1993) also found that drivers adapt their in-car glance durations according to the driving task demands by shortening individual glance durations with increased driving demands. More specifically, our proposed strategy posits that drivers adapt their time limit for in-car glance based on the driving environment immediately upon returning to the driving task: if the vehicle is stable and "well-placed" in the lane, drivers increase the limit, under the notion that perhaps they could have done more searching; if the vehicle is unstable and/or badly displaced from the lane center, drivers decrease the limit, under the notion that the current limit was too long and resulted in a less desirable situation. The details of this process are further quantified in the model below.

2.3. Cognitive model

The above sections provide a description of the overall strategy for visual sampling while driving; however, we desire a more rigorous formulation to facilitate testing and direct comparison to

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