Evaluation of the Visual Demands of Digital Billboards Using a Hybrid Driving Simulator

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Digital billboards (DBBs) are designed to present a virtually limitless stream of information intended to acquire the attention of passing motorists. Unfortunately, very little published research has been conducted to examine how much information drivers can extract during these epochs, or how the acquisition of this information impacts driving performance. Large-format signs are difficult to study using conventional driving simulators because their displays lack the spatial resolution needed to adequately render signs at distances greater than 100-ft. The current study used a hybrid video/mechanical driving simulator to overcome such limitations. Lane keeping, eye gaze position and reading performance were monitored while participants read digital billboards displaying 4, 8 and 12 words while traveling at 25 and 50 MPH. Results indicated that drivers gradually drift away from the centerline during the DBB inspection interval, and then execute large / sudden compensatory steering inputs to re-establish their position in the center of the lane after the billboard had been overtaken. Conditions leading to visual processing overload are identified and some preliminary guidelines for the design and placement of roadside DBBs are proposed.

INTRODUCTION

Though legislation has been enacted to control outdoor advertising signs, much of it was written when large, *static* billboards dominated the landscape adjoining the interstate system (1950s – 1990s). Over the last 10 years, advancements in sign technology have led to a significant influx of *digital* billboards (DBBs) and advertising signs that now populate both rural and urban roadways. And while the location of DBBs is subject to the same controls as static advertisements, no rules have yet been enacted to regulate how digital signs should function in the field (e.g., information given per unit time). Even when local ordinances are enacted to govern digital signs, they are often stated colloquially (e.g., the sign cannot be “too bright”), and without reference to empirically-derived guidelines

In contrast to static advertisements, on which only a few words are typically presented, DBBs are also designed to project a virtually limitless stream of information to nearby motorists. This effectively forces drivers to remove their gaze farther from the forward view of the roadway in order to acquire new content as it is presented upon approach. In doing so, the normal symmetrical processing of the optic flow in the visual environment becomes increasingly asymmetric, a condition leading to erroneous heading estimation and a decreased ability to maintain baseline steering performance (Gibson & Crooks, 1938; Hildreth et al., 2000; Land & Horwood, 1995; Readinger et al., 2002; Telford & Howard, 1996).

Beijer, Smiley, and Eizenman (2004) recorded the eye movements of drivers as they traversed the Gardiner Expressway, a heavily-traveled and advertisement-rich corridor in Toronto, Canada. The focus of this research was to determine both the length of time and frequency upon which motorists attend to various forms of advertising signage. Findings indicated that 88% of participants made long glances while driving (> 750 ms), and that 78% of all long glances were projected upon *active* advertising billboards (i.e., scrolling or video). Much like Beijer’s (2002) study, it was also discovered that active roadway signage incurred a significantly greater number of total glances than did their static counterparts.

Upon examining the same segment of highway in Toronto, Canada, Smiley and her colleagues (2005) noted that active advertising billboards were also able to elicit unsafe looking behavior from passing motorists. This study determined that 20% of all long glances (> 750 ms) were made towards video advertising signs, and that 25% of these long glances were projected at eccentricities up to and exceeding 20 degrees. During several of these instances, drivers fixated video advertising signs for durations longer than 1.5 seconds.

Because digital billboards are able to render large amounts of information, attempting to extract their content may force drivers to remove their eyes farther off of the roadway as they approach the sign. Studies have shown that drivers are able to safely view roadway signage for relatively long periods of time *if* the sign is positioned at a relatively narrow angular offset from the centerline of the road (Schieber, Burns, Myers, Gilland, & Willan, 2004). However, human observers are inaccurate in assessing their heading while looking at large offsets from the direction of travel (Telford & Howard, 1996; Readinger, Chatziastros, Cunningham, Bulthoff, & Cutting, 2002), and drivers perform significantly worse when attempting to navigate a motor vehicle in the absence of visual feedback (Hildreth, Beusmans, Boer, & Royden, 2000); both likely scenarios when one allocates visual resources away from the roadway and onto lengthy digital advertisements.

Current Study

Video-based driving simulators are not well suited for studying a driver's ability to extract information from signs at the same distances at which drivers can perform such tasks in the real world. These simulators lack sufficient display resolution to render sign stimuli that are readable at a distance. In the study reported here, we designed, built and evaluated a specialized hybrid simulator for investigating the limits of sign reading performance while driving. The driving task and its central visual environment (i.e., the road ahead) was implemented using a validated, commercial driving simulator; while the DBB stimulus was implemented via a separate 20:1 scaled LCD display mounted on a linear actuator rail that could move the simulated DBB toward the observer at angular velocities simulating speeds up to 55 MPH. Based upon this hybrid approach, the current study sought to evaluate driving performance exhibited while reading digital billboard messages of various lengths. The amount of information extracted (i.e., read aloud) as well as eye gaze direction data were recorded throughout the duration of each trial. The findings of this preliminary study are reported below.

METHOD

Participants. 18 participants were recruited from undergraduate university classes (7 males; 11 females; mean age = 21.8 years). Participants had corrected visual acuity of 20/28 or better.

Apparatus. A Systems Technology STISIM simulator was used to implement a simple driving scenario consisting of a rural three-lane highway. Participants were required to guide the vehicle down the center lane while obeying the posted speed limit. The STISIM's visual output was rendered on a single, color LCD display that subtended approximately 40 degrees. To the right of the STISIM display, a 20-ft long linear actuator rail was placed so that it could be used to simulate a DBB path-of-travel that was approximately 300-ft long and offset 30-ft from the virtual roadway (assuming a 1:20 lab-to-world scale). A high-resolution LCD display was mounted on the linear actuator rail via a set of bearings (attached to a motor driven belt). A computer controlled stepping motor was employed to drive the LCD display up and down the actuator rail in a smooth and consistent fashion – simulating a moving 10-ft wide DBB at speeds up to 55 MPH. Text characters on the DBB simulator were displayed at high contrast and brightness (greater than 85% @ 85 cd/m^2). All text characters were 0.5-in tall and subtended 9.5 minarc at the maximum DBB simulation distance of 300-ft (the same size as a 20/40 acuity optotype). See http://apps.usd.edu/coglab/schieber/eyetracking/hfes2014/hybridsim.html for a video demonstration of an early prototype of the hybrid DBB-driving simulator in action. Finally, a close-up video recording of the participant's face (with audio from a head-mounted microphone) was used to determine relative gaze position (road ahead versus toward the DBB stimulus) using off-line, frame-by-frame video analysis (The validity of this technique was previously demonstrated by Schieber, Harms, Berkhout & Spangler, 1997).

Procedure. Each participant was provided with approximately 10 minutes of practice time driving the simulator (and reading sample DBB messages). The experiment was divided into two blocks. Half of the DBB presentations occurred while driving at 25 MPH while the remaining half occurred while driving at 50 MPH. The order of these speed blocks was counterbalanced across subjects. Within each block, participants were presented with DBB stimuli at predetermined random locations along the simulated roadway. DBBs contained either 4, 8 or 12 words drawn randomly from a pool of words with high frequency usage in the U.S. English language. All words were 4-to-5 characters in length. Each of the three DBB message lengths was repeated 4 times within a block. DBB message length/replication order was randomized. Each experimental trial began with a signal being sent from the STISIM driving simulator to a purpose-build controller that modulated the motion of the DBB display. The stimulus message

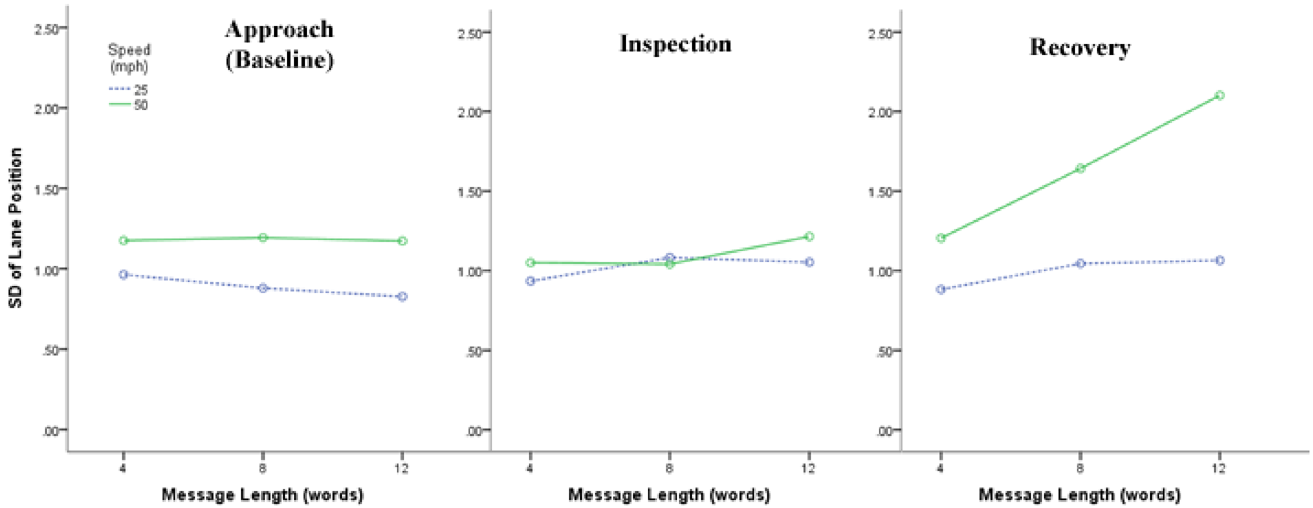

Figure 1. Standard deviation of lane position as a function of observation epoch, digital billboard message length and simulated driving speed.

was presented on the DBB display that was previously positioned at a simulated distance of 300-ft and then immediately began moving toward the participant at a simulated speed of either 25 or 50 MPH (depending upon the experimental condition). The message was erased at the end of the run and the controller slowly returned the blanked DBB display back to the home position in preparation for the next trial. The participant was required to read aloud as many words as possible while still maintaining adequate control of the primary driving task.

The simulator time-stamped and recorded driving performance data for 8 seconds prior to DBB message onset (Approach epoch), while the DBB was in motion (Inspection epoch) and for 8 seconds following the termination of the DBB message (Recovery epoch). Audio/video data streams were time-stamped and recorded for off-line analysis of eye gaze location and scoring of the number of words successfully read on each DBB stimulus trial.

RESULTS

Analyses reported here are limited to lane keeping performance, reading accuracy and eye glance behavior. The standard deviation of lane position was analyzed using a (2) Driving Speed {25 vs. 50 MPH} by (3) Message Length {4, 8 and 12 words} by (3) Driving Epoch {Approach; Inspection; Recovery intervals} repeated-measures analysis of variance. All three main effects were highly significant. However, due to space limitations, attention will be limited to the decomposition of the significant 3-way interaction effect ($\mathbf{F}(4,68) = 3.14$, $p < 0.02$) which is graphically depicted in Figure 1. Reference to baseline performance depicted in the left-panel of Figure 1 reflects the finding that lane keeping was significantly better at 25 MPH compared to 50 MPH ($p < 0.001$). The fact that lane keeping performance did not vary with message length meets nominal expectations since this data was collected BEFORE the digital billboard message was encountered. During the inspection interval while the observer was actually reading the sign (middle panel), the lane keeping performance advantage of slower driving disappeared. However, lane keeping performance was not negatively affected by increases in DBB visual demand as message length increased from 4 to 12 unrelated stimulus words. Somewhat unexpected was the finding that lane keeping performance decrements associated with the visual demands of DBBs did not emerge until the recovery interval immediately after reading the sign (see the right-panel of Figure 1). During the 8 seconds immediately following the DBB encounter, lane keeping performance returned to baseline levels in the low speed (25 MPH) condition but was significantly reduced at the higher speed (50 MPH). This performance decrement was statistically significant at all levels of the message length manipulation (4words: $\mathbf{t}(35)=3.44$, $p<0.002$; 8 words: $\mathbf{t}(35)=5.68$, $p<0.001$; 12 words: $\mathbf{t}(35=7.36$, $p<0.001$). Furthermore, the reduction in lane keeping performance at 50 MPH became increasingly larger as the length of the DBB message became longer (4 vs 8 words: $\mathbf{t}(35)=5.06$, $p<0.001$; 4 vs 12 words: $\mathbf{t}(35)=6.93$, $p<0.001$; 8 vs 12 words: $\mathbf{t}(35)=3.59$, 0.001).

The eye gaze data (total eyes-off-road time; number of glances to the sign) and reading performance data

Table 1. Reading Performance & Eye Glance Behavior

Experimental condition	Mean words read (% of sign content)	Mean number of glances	Mean eyes-off-road time (msec)
4 words/25 mph	3.96 (99)	2.45	2346
8 words/25 mph	7.88 (98.5)	3.27	3676
12 words/25 mph	11.4 (95)	3.99	4803
4 words/50 mph	3.99 (99.8)	2.07	1861
8 words/50 mph	7.54 (94.3)	2.69	2902
12 words/50 mph	9.0 (75)	2.82	3484

collected during the DBB inspection epoch are summarized in Table 1. A (2) Driving Speed by (3) Message Length analysis of variance was performed upon the eyes-off-road time data. The significant speed by message length interaction ($\mathbf{F}(2,34) = 38.0$, $p < 0.001$) is graphically depicted in Figure 2. All *post hoc* pairwise contrasts between the various levels of message length were statistically significant ($p < 0.001$) for both speed conditions. Similarly, the pairwise contrasts of driving speed were statistically significant ($p < 0.001$) at every level of the message length factor. An analogous analysis of variance was also performed on the number of glances to the DBB observed during the inspection epoch. The results of this ANOVA were identical to the eyes-off-the-road time analyses: i.e., the driving speed by message length interaction was statistically significant ($\mathbf{F}(2,34) = 12.39$, $p < 0.001$) as were all possible pairwise comparisons.

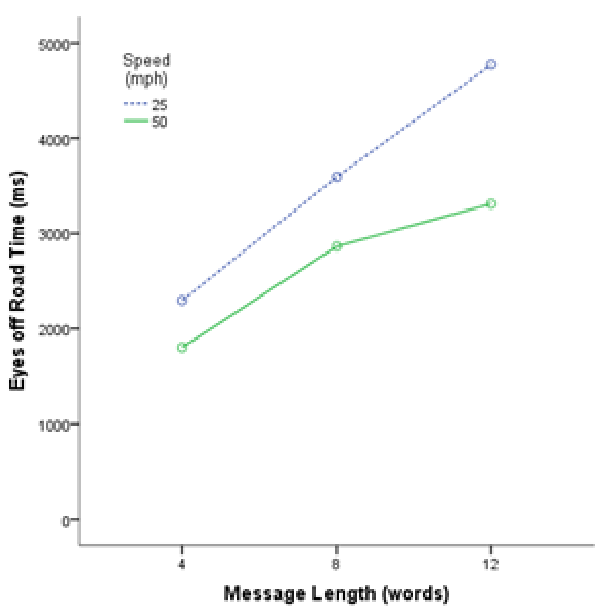

Figure 2. Eyes-off-road time as a function of DBB message length and speed of travel.

A graphical display of data derived from Table 1 can be used to reveal the relationship between eyes-off-the-road time and reading performance. When reading performance is plotted as a function of reading time available per word displayed on a DBB (Figure 3), a sudden performance decrement can be noted when available viewing time dropped below 500 msec per linguistic unit. Asymptotic reading performance was reached when 1000 msec of viewing time per word was available. This asymptote time is much longer than required for normal text-reading and appears to reflect the need to time-share vision with the navigation task.

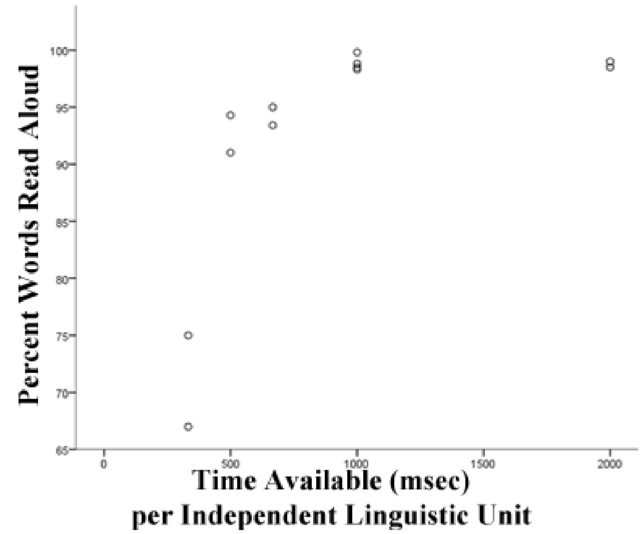

Figure 3. Reading performance as a function of time available per DBB stimulus word.

DISCUSSION

This initial study using a hybrid video/mechanical driving simulation platform suggests that our approach can reveal important information about the effects of reading large-format digital billboards (DBBs) while driving. Although little or no decrement in lane keeping or reading performance was observed at slow speed (25 MPH) on straight roads, clear evidence of impaired performance became apparent at the higher driving speed (50 MPH).

Lane keeping performance was significantly degraded when participants were required to read DBBs with 8 or more words at 50 MPH. This decrement was especially noteworthy when 12 words appeared on the DBB display. Curiously, these decrements in lane keeping performance (increases in SD lane position) emerged AFTER the participants had finished reading the sign. *Post hoc* analyses were conducted to better understand the nature of this somewhat unexpected migration of performance decrements from the Inspection epoch to the Recovery epoch. These analyses revealed that instead of weaving back-and-forth on the road while reading the DBBs with 8 or 12 words, participants tended to “slowly” drift away from the center of their lane and then execute a large amplitude corrective steering input during the Recovery interval (8 seconds after encountering the DBB stimulus). As would be expected, the standard deviation of lane position metric was somewhat insensitive at discriminating between these two modes of steering error but our *post hoc* analyses revealed that the maximum first derivative of lane position clearly detected such compensatory turbulence in the post-DBB encounter.

The eye gaze statistics and reading performance data suggest that information processing overload began to emerge at a message length of 8-words and was clearly present when encountering 12-word DBBs under the high speed condition. That is: the proportion of words extracted from the DBB dropped by 5% at 8-words and all the way down to 75% for 12-word DBBs encountered at 50 MPH. The non-linearity in eyes-off-road-time as a function of increasing message length at 50 MPH (see Figure 2) can be interpreted as a clear indication that participants did not have enough time available to process all of the stimuli in the 12-word DBB condition. The qualitative analysis of reading performance as a function of visual processing time available per stimulus word (see Figure 3) indicated that reading performance began to suffer when processing time allocations dropped below 500 msec/word. Optimal reading and lane keeping performance occurred at 1000 msec/word under these dynamic, dual-task viewing conditions. At this point it should be noted that the use of isolated word stimuli (instead of complete sentences) in this experiment introduces some reductions in ecological validity. However, this approach allows our results to be more easily generalized to other modeling applications since each word represents a distinct linguistic unit of information and it reduces variability due to idiosyncratic semantic differences within and across stimulus demand conditions.

Finally, the findings of the current study provide a basis for the formulation of some design guidelines for the deployment of DBBs in the roadway environment. These are listed below. Additional work will be required to extend these guidelines to dynamic displays such as multiple-page formats and real-time video. In addition, future efforts will need to simulate the demands of surrounding traffic as well as the DBB's visual load. The hybrid driving simulator appears well suited to supporting such efforts.

Preliminary DBB Design Guidelines

No more than 8 linguistic units (i.e., content words) should be presented at a time for low-speed roads (25 MPH); with a maximum of 4 content words on high-speed surface roads (50 MPH).

Optimal reading-while-driving requires at least 1000 msec of exposure time per content word displayed.

At least 500 msec per content word is necessary to avoid significant decrements in reading performance.

Placement decisions for DBBs must consider environmental demands imposed upon drivers in the "recovery zone" immediately beyond the sign's location (e.g., other signs; parking lot entrances, etc.). This migration of DBB effects to the 8 sec of travel *beyond* the sign is perhaps the most unexpected finding of the current investigation.

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