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Stacie Granada

Arik Quang Dao

Dominic Wong

Walter W. Johnson

Vernol Battiste

DEVELOPMENT AND INTEGRATION OF A HUMAN-CENTERED VOLUMETRIC COCKPIT SITUATION DISPLAY FOR DISTRIBUTED AIR-GROUND OPERATIONS

Stacie Granada and **Arik Quang Dao**
San Jose State University
Moffett Field, CA

Dominic Wong
QSS Group Inc.
Moffett Field, CA

Walter W. Johnson and **Vernol Battiste**
NASA Ames Research Center
Moffett Field, CA

In the Distributed Air Ground Traffic Management (DAG-TM) simulation environments pilots flew desktop simulators, which included a Cockpit Situation Display (CSD). Within the current paper we will briefly review the tasks pilots were responsible for in the simulations and subsequently evaluate the tools made available on the CSD to assist the pilots in executing their tasks. Some of the tasks pilots were responsible for in the simulations included the following: to create and evaluate user-preferred routes, meet flight scheduling requirements at the meter fix, self-space behind designated aircraft, and maintain separation with other aircraft. Some of the tools offered within the CSD to facilitate these tasks included a Route Analysis Tool (RAT), a Waypoint table with capabilities to input scheduling requirements, a Spacing tool, and Conflict Detection and Alerting logic. A detailed examination of these features and others will be discussed

In 1995, the RTCA Task Force 3, Free Flight Implementation (1995) cited a need for a Cockpit Display of Traffic Information (CDTI) that could increase situation awareness on the flight deck in order to develop and progress the notion of free flight. While numerous definitions of free flight have surfaced, a seminal view expressed in the final report was that *any* move toward removing restrictions on behalf of the user is a step toward free flight. In order to support free flight, the task force suggested that a CDTI needed to provide information that would allow the flight deck to maintain separation with other aircraft, perform rerouting operations en route, and engage in limited delegation to maintain spacing en route or in the terminal area.

The NASA Ames Flight Deck Display Research Laboratory has devoted many years of research and development to a Cockpit Situation Display (CSD; a high fidelity aviation navigational display) due to the increase in endorsements toward advanced flight deck displays by the FAA and NASA's Advanced Air Transportation Technologies (AATT) program (Johnson, Battiste, & Holland, 1999). Work on the Ames 3D CSD described in this paper was conducted for two reasons. First, there is an accepted need for displays that provide vertical and horizontal situation information. In an assessment of both these display formats, Wickens, Olmos, Chudy, & Davenport (1997) found that information about relative altitude was not naturally available when viewing traffic on a horizontal situation display, and lateral position information was not available on vertical situation displays. In today's flight deck where display space is at a premium, having a single display to view both vertical and horizontal situation information seems to be the practical solution.

Second, an advanced flight deck display was needed to facilitate the examination of potential free flight concepts. In order for Air Traffic Controllers (ATC) to manage higher traffic flows they will not only need advanced tools on their end, but they also will need pilots to share in some of the air traffic management roles and responsibilities. By providing a tool such as a CSD on the flight deck pilots can maintain better situation awareness, which inadvertently gives ATC greater flexibility with what options they can use to manage their own workload, such as with having pilots manage to a required time of arrival at the meter fix. Overall, an advanced flight deck system is needed to facilitate the examination of free flight concepts.

Multiple simulations were conducted at NASA Ames Research Center to examine Distributed Air Ground Traffic Management (DAG-TM) solutions for free flight. These proposed solutions aimed to examine three concept elements - CE-5: En Route Free Maneuvering; CE-6: En Route Trajectory Negotiation; CE-11; Self-Spacing for Merging and In-trail Separation for Terminal Arrival - which were designed to evaluate various roles and responsibilities by which free flight could be achieved (Battiste et al., 2005; Johnson et al., 2005). The goal of the current paper is to review a Decision Support Tool (DST; specifically, the Ames 3D CSD) utilized by pilots in these simulations. The main tools developed within the Ames 3D CSD are described in detail. We address some of the benefits of the Ames 3D CSD and the tools within the CSD, both of which provided the platform with which we could test the concepts proposed under DAG-TM.

The CSD and DAG-TM

The goal of DAG-TM was to propose a prototype of an air/ground system with a human-centered approach. That is, the research team reevaluated the roles and responsibilities of the stakeholders to enhance user flexibility and user efficiency with, for example, user-preferred routing to increase airspace capacity without impeding upon safety or airspace accessibility.

Within the concept elements tested, pilots flew desktop simulators and were responsible for the following tasks: 1) maintaining separation 2) meeting their assigned RTA (Required Time of Arrival) 3) modifying Ownships flight path for traffic and RTA compliance 4) sending and acknowledging trajectory changes, and 5) self-spacing behind a designated lead aircraft. Several DSTs were provided to aid pilots in accomplishing these new tasks and to meet their responsibilities in the simulations. The remaining portion of this paper addresses the Ames 3D CSD, which provided pilots with the ability to achieve the tasks outlined above.

CSD Display Overview

The primary DST for the flight deck was the 3D CSD (see Figure 1), which dynamically depicted traffic, flight plans, conflicts, and more. With this airside interface, pilots had the ability to view traffic information in a planar view, profile view, and to dynamically position the display in some combination between these two choices with a 3D perspective. An earlier paper describes some of the features of a previous 2D version of the CSD in detail (Johnson, Battiste, & Holland, 1999).

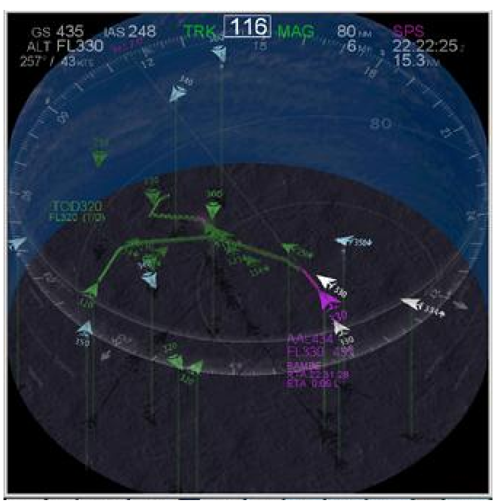


Figure 1. *3D CSD; to view pictures in color or to download a demo version see the web address in footnote 1.*

The goal of the Ames 3D CSD was to integrate several tools into a single interface and expand the user's situation awareness by providing a 3D depiction of the airspace. 3D displays have some advantages compared to 2D displays. First, 2D planar displays do not visually render altitude information in as optimal a manner as was desired. It is possible to use coplanar displays exhibiting both top down and profile views of traffic, but they use excessive display space and cannot depict some conflict geometries. It was intended that pilots have the ability to view any and all geometric traffic situations, thus the display needed to have the ability to depict any and all geometric traffic situations. Second, future work with the current CSD will include the integration of traffic, weather, and terrain within the same display. 3D renderings may provide more realistic depictions of weather and terrain, as well as provide greater global situation awareness within the flight deck.

CSD - Display Basics. Due to limited space, only the key components of the DSTs within the Ames 3D CSD are described in this paper[1]. In general, the Ames 3D CSD presents the standard navigational elements at the top-most portion of the display and Ownship is depicted as magenta.

The Ames 3D CSD offers two modes in which a user can view traffic. At start-up, the primary display projection (the standard view) is set in *Expanded mode, planar view*. In this mode a compass rose, depicted at the top-most portion of the CSD, displays 100 degrees of heading value with Ownship depicted at the center of the display. In the *Expanded mode*, the user can only view the CSD in a 2D top-down (i.e., planar) view. When the display is switched to *Full mode*, the user can manipulate the CSD to examine the display as a 3D depiction on a 2D surface (i.e., perspective display). In this mode, the compass rose is displayed as a full 360 degrees around Ownship (except in temporal view, which is described below).

The benefit of providing the Full mode in the Ames 3D CSD is that two projection views are offered: *Orthographic* and *Perspective*. From the orthographic view, the sizes and perspective of elements on the screen are discrete and constant which makes it easier for the viewer to make judgments regarding the distance and direction of the aircraft on the display. In contrast, the perspective view affords making relative judgments regarding the

[1] For more information, download the Ames 3D CSD User Guide at http://human-factors.arc.nasa.gov/ihh/cdti/download.html

relative distance between aircraft; as aircraft that are farther away diminish in size.

In addition to orthographic and perspective views, the full mode provides a *Central* and *Temporal* view which are dependent upon the relative position of Ownship. The *Central* view positions Ownship in the center of the rings on the display affording detection of aircraft by a distance parameter around the Ownship. The display range provides the ability for pilots to zoom in for a detailed look at the airspace around Ownship (10nm) or zoom out as far as 640nm to facilitate in viewing or planning far-term trajectories. Table 1 lists the display range tool and indicates how usable and useful pilots in the simulations found this tool.

The *Temporal* view positions Ownship closer to the bottom edge of the display, which maximizes the view in front of Ownship. The depiction of traffic is relative to a time parameter, where for example, any aircraft displayed can reach Ownship within 10 minutes.

The Ames 3D CSD provides four memory settings whereby users can set and quickly flip through multiple views. For example, a user may choose a top-down planar view of the traffic, a vertical rear-view, a vertical side-view (or profile view), and a 3D view. With visual momentum, the display will move into any of the preference settings by simply clicking the corresponding buttons. Additionally the display can be manipulated into any 3D view by simply right clicking and dragging the display toward the desired angle. Although it is not likely that a mouse will be used on a flight deck to manipulate such a display, this input device works for simulations and other control devices can eventually adopt similar strategies for acquiring display motion. Further research is needed to explore this issue as implementation of CSDs come closer to reality.

Usefulness of the display. Research shows that there are advantages and disadvantages to 3D displays and 2D coplanar displays, and the benefits of each are task dependent (Wickens, Olmos, Chudy, & Davenport, 1997). The 3D CSD outlined here has the benefit of being manipulated to display a top down view of the traffic situation, a profile view, or *dynamically* moved to display some rare conflict geometries that are not discernable from simple 2D or coplanar displays. Having the option to view traffic from several viewpoints allowed pilots to look ahead at any conflict situation and determine where the paths of two aircraft would cross while searching for an efficient route through the meter fix. In the DAG-TM simulation of autonomous flight operations, pilots flying in an Advanced Concepts Flight Simulator (ACFS) and those flying single-pilot stations (both using Ames 3D CSDs) were able to meet their meter fix crossing restrictions while maintaining separation with other aircraft (Kopardekar et al., 2004). Pilots reported using the Ames CSD in 3D 36% of the time and in 2D 64% of the time. Table 1 provides pilots' ratings of features within the Ames CSD in terms of usability and usefulness (each item is addressed in the text).

Table 1. *Pilot Ratings of CSD Tools*

Tool	**Usability**		**Usefulness**	
	M	SD	M	SD
Display settings				
Display range	4.9	0.32	5.0	0.00
3D View	4.2	1.14	4.1	1.29
Route information				
3D flight plans	4.3	1.34	4.7	1.00
Path predictors	5.0	0.00	4.7	0.67
RAT features				
RAT path	4.5	0.53	4.6	0.70
RAT: drag/drop	4.5	0.85	4.6	0.84
Alerting system				
Alert warning	4.5	0.71	4.5	0.71
Alert symbology	4.4	0.52	4.0	1.05

N = 10; Scale: 1 = not very usable/useful, 5 = very usable/useful.

Pilots found the display range, 3D views, and 3D flight plans usable and useful. Overall, the 3D display settings provided pilots with enough situation awareness to maintain separation and make strategic flight modifications, and the pilots seemed to like these features.

CSD - Aircraft Intent. With the Ames 3D CSD, properly equipped aircraft (i.e., those with Automatic Dependent Surveillance Broadcast, ADS-B) have the ability to transmit and receive intent information, or flight plan information, from aircraft within ADS-B broadcast range. The Ames 3D CSD allows users to view intent information in two ways. First a user may choose to display the entire flight plan of one or more aircraft on a case-by-case basis. Flight plan intent information is depicted as a linear path relative to the direction of the aircraft heading and includes information regarding level flight and descent or ascent segments of flight. To view the flight path of an aircraft, a user must simply click on the aircraft symbol within the CSD and the flight path is rendered on the display. Again, for specific details regarding intent depiction see the Ames 3D CSD User Guide (http://human-factors.arc.nasa.gov/ ihh/cdti/ download.html).

The second option to view intent is for users to display "fast-time predictor" information simultaneously for *all* or selected aircraft within the selected altitude surveillance band and broadcast range. Fast-time predictors are shown along the depicted flight path of all or selected aircraft. The users can select the amount of time they would like the intent information "forecasted". That is, traffic may be displayed with path intent information ranging from 0 to 20 minutes ahead. The fast-time predictor is shown as a pulse traveling the length of the predictor line(s) and reflects the speed the aircraft are flying. Due to the nature of flight, intent information may change at any moment. Intent information is depicted for the "current" status of the aircraft and updates as the flight status for each aircraft changes.

The pulse predictor also traverses any flight plan (option 1 from above) that is selected by the user as long as the pulse predictor is set anywhere from 2 – 20 minutes. The major distinction here is that flight plan information yields *all* of the aircraft's registered intent information, whereas the predictor lines only show up to 20 minutes of intent information. Again, the flight plan of individual aircraft may be turned on or off by clicking on the desired aircraft symbol, then the predictor can be turned on for the selected aircraft, or on for all aircraft.

Usefulness of aircraft intent. There are benefits associated with the predictor tool and having access to visualizations of entire flight plans. For example, Xu and Rantanen (2003) demonstrated that perceptual cues regarding motion prediction afford less error in collision estimations. This supports the notion that the predictor tool can offer robust situation awareness in detecting conflicts as it provides perceptual information regarding future locations of the target aircraft. That is, combined with a 3D display the pulse predictor provides 4D flight information, which fosters low workload for examining the threat potential of existing traffic.

Additionally, as users have access to rendering of full flight plan information they are less likely to fall subject to the perceptual illusions. Research has demonstrated that there are particular geometric collision angles that may elicit a bias in position prediction and create a false sense of safety when predictor lines are short (Comerford & Uhlarik, 2001; Holland, 1998). Therefore, the full flight plan implementation allows the user to scrutinize possible conflicts more closely for safer operations. As Table 1 indicates, pilots found the flight plans and pulse predictor tool highly usable and useful.

CSD - Route Assessment Tool (RAT). The RAT provides the user with the ability to create and visualize in-flight route modifications, submit proposed route modifications to ATC, receive route modifications from ATC, and execute any of these modifications depending on flight status. The planning and implementation of these flight plan modification possibilities are subject to provisional alerting and are made available for 1) strategic conflict resolution, 2) RTA requirements, 3) weather avoidance, 4) direct route efficiency, 5) dynamic Special Use Airspace (SUA) avoidance, and eventually 6) terrain avoidance.

To perform any of the functions outlined above, the user must first turn the RAT on by clicking the RAT button on the CSD toolbar. This provides the user with access to a waypoint table, a flight path that can be manipulated (see Figure 2), and options for execution or datalink. The RAT tool allows the user to enter new waypoints or to use the waypoint table to scroll through existing waypoints.

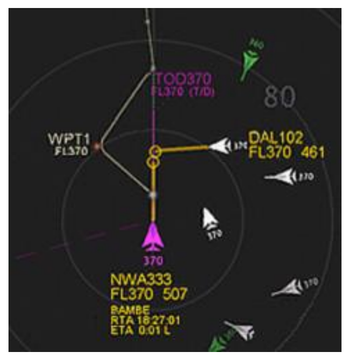


Figure 2. *Route modification with RAT*

Once a waypoint is identified, the user can enter an RTA for the waypoint, enter a new altitude for that waypoint, or move the waypoint to a new lateral position. All of the RAT functions can be visualized and evaluated before execution, which helps reduce the need to make numerous changes to the flight plan since pilots can verify whether the modification reflects the desired action.

Usefulness of the RAT. In the recent DAG-TM simulations, the RAT allowed pilots to solve conflicts strategically as opposed to tactically. That is, pilots were able to modify their flight plans to avoid a loss of separation (Kopardekar et al., 2004), whereas with existing TCAS systems, collision threats can only be avoided tactically when the threat is imminent.

The RAT provided an easy method for visualizing, manipulating, and changing flight information, which required little mental effort or calculations on behalf of the flight crew. For example, if a pilot wanted an altitude change, the only work required by the crew was to insert a start point on the flight path and to enter the newly desired flight level. The aircraft's most economical climb or descent is determined by the system and is based on how large the change in altitude is. Since the RAT provides immediate visual feedback and provisional alerting information, flight crews know whether the proposed flight change will have an adverse impact on safety before executing the plan, and can continue to visually search for path variations until a safe trajectory is found. In the recent DAG-TM simulations, pilots were able to use the RAT to strategically solve conflicts when the traffic levels exceeded the capacity of today's airspace (Kopardekar et al., 2004). Table 1 also indicates that pilots found the design of the RAT path and the drag and drop features of the RAT to be usable and useful.

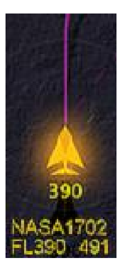
CSD - Alerting. The Ames 3D CSD alerts are depicted for strategic conflict detection as opposed to tactical conflict detection. This type of alerting is designed to encourage less drastic changes to the flight plan in order to resolve the conflict to help reduce time, cost, and to increase safety. The alerting logic detects conflicts (or losses of separation) based on an algorithm of temporal proximities, which takes into account the aircraft intent information or aircraft state information (current heading, altitude, speed). For more detailed information regarding logic behind the Conflict Detection and Resolution within the CSD see Canton, Refai, Johnson, and Battiste (2005).

The CSD depicts 3 levels of alert (See Figure 3a, b, c). Alert level 1 is the lowest level of alert and is depicted on the CSD when Ownship and the conflicting aircraft become yellow or amber. At Alert Level 2, an amber glow is added to the existing Alert Level 1 symbology. Finally at Alert Level 3, yellow predictor lines with intersecting Loss of Separation (LOS) rings are added to the alert symbology. These depictions provide information regarding how imminent any particular alert may be.

Figure 3a

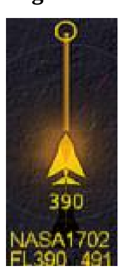
Alert Level 1

Figure 3b



Alert Level 2

Figure 3c



Alert Level 3

Usefulness of alerting. The alerting techniques utilized by the CSD were useful in providing enough information to keep pilots aware of possible safety concerns (i.e., possible losses of separation) without committing to numerous false alarms (Kopardekar et al., 2004). Xu (2003) recommends that effective alerting systems provide continuous measures of conflict detection as opposed to dichotomous measures. That is, rather than provide pilots with an all or nothing view of whether a conflict is likely, it is beneficial to utilize and consider the dynamics of flight. Again, the alerting system outlined here took into account winds, future flight plan information (such as a descent profile), and the alert level based on proximities. Additionally pilots had access to the time-to-contact information (with early notification), which overall contributed to the pilots' ability to view possible conflicts at farther time increments, allowing strategic resolutions rather than tactical. As with the other CSD tools, Table 1 indicates that pilots found the alert warning and alert symbology usable and useful.

CSD - Spacing. The CSD allows users to self-space behind designated lead aircraft (e.g., maintain 90 seconds behind aircraft XYZ). With the spacing tool users can input the assigned spacing value while algorithms work to adjust Ownship's speed in order to maintain the required interval (Abbott, 2002).

The CSD renders a spacing box that represents the target location of Ownship based on the spacing interval that was set. This provides the user with updated visual information regarding the current spacing status. For example, if Ownship is targeted at the correct interval behind its lead aircraft, the spacing box will appear green and Ownship will visually appear *in* the box. Similar visual feedback is provided if Ownship is too early or late for its spacing assignment. A temporal indication of the spacing status also appears in Ownships data tag when the spacing is set.

Usefulness of spacing. In the DAG-TM simulations, pilots were able to effectively use the spacing tool and they found workload to be low when spacing clearances were issued early (Battiste et al., 2005). With the spacing tool available on the Ames 3D CSD, it is possible to test several concepts aimed at improving airspace bottlenecks as aircraft transition from en route through the meter fix into the terminal area.

Ames 3D CSD Effectiveness

Overall, the Ames 3D CSD utilized in the DAG-TM simulations provided pilots with the type of situation awareness necessary to effectively maintain separation, meet their assigned RTA, modify Ownships flight path, send/acknowledge trajectory changes, and self-space behind designated lead aircraft.

The tools within the Ames 3D CSD offered a flexible and comprehensive backbone of information that pilots could use in testing the autonomous operations, self-spacing spacing operations and more. In this simulation we had the opportunity to evaluate how pilots interacted with the aforementioned tools and how they in turn facilitated flight in this futuristic free flight concept (Kopardekar et al., 2004). The data indicated that flight crews flying the ACFS and pilots flying the single (desktop) station CSDs were able to meet their assigned RTA's as well as the speed and altitude restrictions at the meter fix, whether they were under ATC control or operating autonomously. It is also worth noting that an increase in traffic did not alter the CSD pilots' performance in meeting these requirements. Finally, all CSD pilots were able to maintain separation with both the managed and autonomous aircraft, even with the increase in traffic. This demonstrates the potential for free flight concepts with the use of CSDs, such as the one described here.

The Ames 3D CSD presented here has incorporated visually dynamic traffic information, such as aircraft intent, route planning, and conflict alerting. Future work will address the integration of traffic, weather, and terrain on a 3D display. Preliminary work on incorporating weather into the CSD is currently undergoing investigation, and recommendations have been made regarding possible design issues to consider for this type of integration (Comerford, 2004).

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THE COSTS AND BENEFITS OF HEAD-UP DISPLAYS (HUDS) IN MOTOR VEHICLES

Lisa Hagen, **Matthew Brown**, **Chris M. Herdman**, and **Dan Bleichman**
Centre for Applied Cognitive Research
Carleton University
Ottawa, Canada

Research in the aviation domain has shown that Head-Up Displays (HUDs) can facilitate performance in specific tasks such as controlling aircraft flight path and altitude (Fadden, Ververs, & Wickens, 2001; McCann & Foyle, 1995; Martin-Emerson & Wickens, 1997; Wickens & Long, 1995). However, there are a number of simulator-based studies suggesting that pilots may focus, or *cognitively tunnel* their attention on HUD symbology, resulting in performance decrements in tasks that require continuous monitoring of information from the outside scene (Foyle, Stanford, & McCann, 1991; McCann, Foyle, & Johnston, 1993), and in extreme cases, severe impairment or even failure to detect potentially critical discrete events in the external scene (Brickner, 1989; Fischer, Haines, & Price, 1980; Wickens & Long, 1995). In the present research, we extended our examination of aircraft HUDs to the domain of motor vehicles. Participants drove a high fidelity, fully configured driving simulator through a realistic scenario containing both urban and rural (highway) roads. Speed limit (and other) signs were posted. Two conditions were compared. In the no-HUD condition, a standard in-vehicle instrument panel was used. In the HUD condition, the instrument panel was augmented with a HUD showing digital speed on the windshield. The results showed a benefit of the HUD insofar as participants were better at maintaining their speed in the HUD than in the no-HUD condition. However, this benefit was accompanied by a cost in that participants showed significantly greater deviations in maintaining lane position when the vehicle's speed was available on the HUD than when it was not. This finding suggests that HUD symbology distracts motor vehicle operators to the extent that they are less able to process information from the navigation environment.

Introduction

HUD technology, traditionally used in aircraft, has been implemented by various automobile manufacturers to project vehicle status information onto the windshield (e.g., speed, warning lights). Although there is thorough research on the efficacy of HUDs in aircraft, relatively little work has been done on the impact of HUDs in motor vehicles.

In the present research, the impact of a digital HUD speedometer on driving performance was assessed using a high-fidelity driving simulator. To quickly preview the results, the present study shows that although this particular HUD improved a driver's ability to monitor speed, it impaired their ability to maintain lane position. This trade-off is explained in terms of cognitive tunneling.

Theoretical Benefits and Costs of HUDs

The benefit of HUDs, whether they are implemented in aircraft or in cars, is that they allow the user to monitor vehicle status without *physically* interfering with their ability to view the navigation environment. In theory, HUDs should provide the driver with more time to attend to events in the navigation environment. However, findings from studies testing the effects of HUDs in aircraft suggest otherwise (e.g., Herdman & LeFevre, 2003; McCann & Foyle, 1995). These studies showed that pilots have more difficulty detecting objects/events in the navigation environment when HUD information is available, relative to when it is not. One explanation for this counter-intuitive finding is that pilots are susceptible to a cognitive tunneling effect when a HUD is available. That is, the HUD symbology captures (and holds) the pilot's attention, subsequently preventing them from attending to other events in the navigation environment.

Cognitive Tunneling and HUDs in Automobiles

It seems plausible that the inherent costs and benefits of HUD technology observed in aircraft operation would map directly onto the task of driving an automobile. However, the navigation environment faced by pilots is sparsely populated relative to that faced by a typical driver. As such, drivers are required to navigate in environments that require more precise control of their vehicle's position both within lane markings and relative to other cars sharing the lane. It may therefore be the case that the cognitive tunneling effects observed in flight simulation studies (see Herdman & LeFevre, 2003; McCann & Foyle, 1995) are relatively minor both in terms of magnitude and in terms of consequence. The ever-increasing number of HUDs being installed in automobiles magnifies the importance of assessing the (a) extent to which HUDs render drivers susceptible to cognitive tunneling and (b) the subsequent impact on driving performance.

In order to determine whether cognitive tunneling occurs in automobile HUDs, a simulation experiment was conducted in which drivers' performance in terms of their ability to monitor speed and lane position was assessed. The critical (within-subjects) manipulation had two conditions: (1) participants used the manufacturer-equipped analogue speedometer to ascertain speed (no-HUD condition) and (2) the analogue speedometer was augmented with a HUD of a digital speedometer (HUD condition). The participants' driving performance in these two conditions was compared to determine whether HUD information yields costs and/or benefits.

Methods

Participants. Twenty-two Carleton University students participated and either received course credit or $20 remuneration. All participants were assumed to have normal or corrected-to-normal vision. Further, all participants held a valid Province of Ontario driver's license and had at least two years of driving experience.

Design. One critical factor with two levels was manipulated (HUD condition: HUD vs. no-HUD). This factor was counterbalanced across participants such that half received the HUD condition first and the no-HUD condition second. This order was reversed for the other half of the participants.

Apparatus. The experiment was conducted on a high-fidelity, fully configured DriveSafetyTM 500c driving simulator consisting of a (partial) cabin of a Saturn passenger car mounted in front of five flat-screen projectors subtending approximately 22° of vertical visual angle and 150° of horizontal visual angle. The HUD information (i.e., a digital display of the vehicle's current speed) was located 5° of visual angle below the horizon and 10° of visual angle to the left of the center of the driver's field of view. The HUD was light green in color and subtended 4° of visual angle vertically and 2° of visual angle horizontally. Computer-generated engine noise, which changed accordingly with engine speed, and external noise (e.g., passing traffic) were presented on speakers mounted in the cabin or on the cabin platform. The driving scenario was scripted using TCL scripting language that was executed on a PC-based Linux platform and simulated a two-lane highway passing through small towns, mountain passes, and rural farming areas. The scenario was updated at a rate of 30 to 60 Hz and the data were collected at a rate of 5 Hz.

Procedure. Participants familiarized themselves with the controls and operation of the driving simulator during a ten-minute practice session. The HUD was displayed during practice to minimize potential novelty effects associated with its presence during the experimental session. The experimental session consisted of two identical 25-minute trials, except that participants used the HUD to monitor their speed (HUD condition) on one trial, whereas they used the analogue speedometer on the other (no-HUD condition). Participants were instructed to (a) obey all posted speed limits and general rules of the road and (b) keep the vehicle centered in their lane. Participants were debriefed and received appropriate compensation following completion of the second experimental trial.

Results

Two participants were removed from the analyses: one was unable to complete the experiment due to illness and the other misunderstood task instructions. The data from the remaining 20 participants were trimmed such that data at both the beginning and at the end of the experiment (accelerating to the posted speed limit and decelerating to a full stop) were eliminated. Outlier data were eliminated based on the criteria that the participant's lane position deviated 1.8 m (or more) from the center of their lane.

Speed Monitoring Data

Participants' ability to monitor speed was measured by comparing actual speed to the posted speed limits. This measure was calculated by taking the absolute value of the difference between their actual speed and the speed limit. Speed monitoring was significantly better in the HUD condition than in the no-HUD condition $t(19) = 9.0$, $p < .001$. On average, speed in the no-HUD condition deviated from the speed limit by 3.98 MPH, whereas it only deviated by 2.48 MPH in the HUD condition.

Lane Position Data

The ability to monitor lane position is a critical aspect of safe driving, given that the consequences of failing to do so (e.g., crossing into oncoming traffic) are so dire. Indeed, it could be argued that lane position monitoring is more important that speed monitoring in terms of road safety. For this reason, participants' lane position data were logged and subsequently analyzed. The center-most position of the lane was assigned a value of zero and any deviation left of center was recorded as a negative value, whereas deviations right of center were assigned a positive value. Although knowing about possible systematic tendencies to drift in one direction relative to the other could be of some interest, it is beyond the scope of the present research. As such, lane position monitoring performance was calculated by taking the absolute value of their current lane position (which represents the distance from the center of the lane given that the center of the lane was assigned a lane position value of zero). The interesting result here is that lane position monitoring was significantly *worse* in the HUD condition than in the no-HUD condition $t(19) = 4.3$, $p < .001$. On average, participants in the HUD condition drifted .33 m from the center of their lane, whereas participants in the no-HUD condition only drifted .29 m from the center of their lane. This difference of .04 m could represent the difference between a "close call" and a head-on collision.

Discussion and Conclusion

The results from this driving simulation experiment show that when a manufacturer-equipped analogue speedometer is augmented with a digital speed HUD, drivers are better at monitoring their speed, but *worse* at maintaining their lane position, relative to when no HUD is available. These results are consistent with the claim that digital speed HUDs (typical of HUDs used in automobiles) render participants susceptible to cognitive tunneling effects, whereby attention is captured and held by the HUD symbology such that it is difficult (or impossible) to concurrently attend to information in the navigation environment (e.g., lane position).

Although monitoring vehicle speed is important, the consequences of failing to do so pale in comparison to the potentially disastrous outcomes of neglecting one's lane position or not being able to detect objects and/or events in the navigation environment (e.g., a child running into the roadway). As such, the present research suggests that the limited benefits of a digital speed HUD are outweighed by the potential costs associated with not adequately processing information in the navigation environment. It is therefore essential to refine and empirically assess how and what information (if any) should be presented on a HUD so as to maximize driver awareness of vehicle status while minimizing potential cognitive tunneling effects.

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Correspondence should be directed to:
Dr. Chris M. Herdman, Centre for Applied Cognitive Research, Carleton University, Ottawa, ON. Canada, K1S 5B6.

Direct email correspondence to:
chris_herdman@carleton.ca