Comparative study of the effects of auditory, visual and multimodality displays on drivers’ performance in advanced traveller information systems

YUNG-CHING LIU*

Department of Industrial Engineering and Management, National Yunlin University of Science and Technology, 123, Sec. 3, University Road, Douliu, Yunlin, Taiwan 640, ROC

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A simulator study was conducted to compare 16 younger (mean age 22 years) and 16 older (mean age 68 years) drivers’ ratings of workload (time, visual, psychological stress) and performance of navigation and button-pushing (identification of vehicle or road hazards) tasks under both high- and low-load driving conditions when simple or complex advanced traveller information (ATI) was presented visually only, aurally only or by multimodality (visual and auditory) display. For all participants, both the auditory and multimodality displays produced better performance in terms of response times, total number of correct turns and subjective workload ratings than those of using the visual-only display. Participants using the multimodality display also made the fewest errors related to push-button and navigation tasks, and controlled their vehicles properly. The visual display led to less safe driving, apparently because it imposed higher demands on the drivers’ attention. An age effect was found in the present study, with younger drivers performing better and reporting less stress than older drivers. Notably, however, use of the multimodality display significantly improved the older drivers’ performance in the button-pushing task.

1. Introduction

Advanced traveller information systems (ATIS) are among the intelligent vehicle highway system (IVHS) technologies beginning to appear in new vehicles to reduce traffic congestion and energy consumption, and increase mobility and productivity. To achieve these goals, four different subsystems identified by Perez and Mast (1992) are included in the ATIS to provide substantial navigation information while keeping the driver informed about traffic, vehicle, road and roadside conditions and they are described as follows. (1) In-vehicle routing and navigation systems (IRANS): these subsystems of ATIS provide drivers with information about how to get from one place to another in a turn-by-turn format such as distance to the turn, the name of the street to turn onto and turn direction (route guidance navigation). When integrated with an advanced traffic management systems (ATMS), IRANS can provide information on recurrent traffic congestion, and can

*Author for correspondence e-mail: liuyc@pine.yuntech.edu.tw

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calculate, select and display optimum routes based on real-time traffic data such as the distance/time/cost to the destination, and notification of incidents (route information navigation). However, this does not include route guidance. (2) In-vehicle motorist services information systems (IMSIS): provide motorists with commercial logos and signing for motel, eating facilities, service stations and other signing displayed inside the vehicle to direct motorists to recreational areas, historical sites, etc. (3) In-vehicle signing information systems (ISIS): provide non-commercial routing, warning, regulatory and advisory information inside the vehicle. ISIS provide information that is currently available on permanent roadway signs. (4) In-vehicle safety advisory and warning systems (IVSAWS): provide warnings of unsafe conditions and situations on the vehicle/roadway ahead that could affect the driver.

For ATIS to be accepted and used by drivers, it must be designed to be user friendly, and the drivers’ capability successfully to process those information provided by ATIS will serve as a key factor to achieve this ambitious intuition. Therefore, it is important for researchers to devote attention to try to understand drivers’ needs and limitations in accordance with different driving situations and to try to design display product(s) capable of presenting ATIS information to the majority of drivers in a very safe and efficient way.

For drivers, information displayed visually has both advantages and disadvantages (Wickens and Liu 1988, Dingus and Hulse 1993). Drivers prefer navigation systems that can inform them of their current location visually (Streeter et al. 1985), and graphical visual displays are convenient in that they allow operators mentally to ‘zoom in’ on the displayed area, and thus some human factors guidelines have emphasized that the warning information should be presented pictorially (Rasmussen 1980). Dingus et al. (1989) studied human factors issues of using an in-car navigation system, the moving map, and compared the efficiency with that of the traditional paper map. Results showed that drivers used the navigation device effectively and no significant difference appeared in drive time and total travel time (including map study time). However, the drivers’ scan pattern changed and the subjects reduced their average glance time on the central road while using the navigation device, and this is especially true for older drivers (Pauzie et al. 1989). Pauzie et al. (1989) analysed ageing drivers’ behaviour while navigating with in-vehicle visual display systems, and presented these conclusions: (1) glance duration and frequency toward the LCD screen were significantly higher for older drivers, meaning that elderly drivers spent less time looking on the road ahead; and (2) within a given period, the amount of information that can be handled decreases as a function of age. Zwahlen et al. (1988) investigated the safety issues of an in-vehicle visual information display and examined the visual, safety and performance aspects of operating a simulated CRT touch-panel display while driving at a constant speed along a straight road and keeping lateral lane position. Results pointed out that introducing sophisticated in-vehicle displays or controls that require eye fixations of several seconds could raise a serious problem.

Because drivers depend largely on the visual modality for driving-related information (Lansdown 1997), when an ATIS that makes exclusive use of the visual modality is introduced into the vehicle, drivers may experience attentional overload. To compensate for this, drivers tend to drive slowly and cautiously, and exclusively visual displays thus result in slower speeds than other display modalities, e.g. auditory display (Walker et al. 1991).
Auditory displays can be superior to visual displays in presenting navigation and warning information. Walker et al. (1991) conducted a simulator experiment to evaluate seven in-vehicle navigation devices that varied in complexity and mode of presentation, and they found that drivers using auditory navigation devices of either low, medium or high complexity made significantly fewer navigation-related errors than those using visual mode devices. In terms of complexity, the participants using the complex devices drove more slowly than those using the simpler devices, and high-complexity displays were the least preferable. In addition to making fewer driving errors (Wetherall 1979, Verwey and Janssen 1988), drivers using an auditory device also reduced travel distance and travel time (Streeter et al. 1985, Parkes and Coleman 1990).

Research has assessed the workload differences between auditory and visual presentation of information. Labiale (1990) found that workload was reduced when navigation information was presented auditorily, rather than visually, and drivers preferred auditory information. In high driving workload situations, drivers using auditory display did not reduce their speeds as much as those using visual devices (Walker et al. 1991). The omnidirectional nature of auditory displays makes them the most desirable means of presenting alert and warning information. Operators responded faster to voice warnings than to visual ones (Simpson et al. 1985, Sorkin 1987).

According to the multiple resource theory, in a heavily loaded visual display environment, an auditory display will improve time-sharing performance (Wickens et al. 1983). A multimodality display (visual plus auditory) should thus allow drivers to perceive more information without significantly increasing their workload. For safe driving, short auditory information combined with a visual display might optimize perceptual and cognitive performance (Labiale 1990, Dingus and Hulse 1993). Multimodality displays also resulted in better route guidance results (McKnight and McKnight 1992). McKnight and McKnight compared five navigational displays including area map, strip map, position information, guidance information with an audible alarm, and position/guidance information. The results showed that the guidance information with an audible alarm, activated just before a turn, was the best display facilitating the turns. The error rate was 14.3%, while the other systems produced error rates > 30%. Other refinements, such as the use of a simple symbolic display in conjunction with auditory messages that can reduce drivers’ attention demands, have also been suggested (Parkes et al. 1991).

To date, however, most research has dealt with single display modalities or focused on navigation systems only, whereas the effectiveness of a multimodality display in the ATI systems context still remains relatively unexplained. This question is addressed here.

The objectives were to explore whether driver reaction and performance vary as a function of display modality under different driving load or information complexity conditions, and to investigate whether differently aged drivers have different performances when operating different in-vehicle displays.

2. Methods

2.1. Participants
Previous driving performance research (Dingus et al. 1989) has shown that there were only minor performance differences between younger (< 25 years old) and middle-aged (26 – 35 years old) drivers. However, research has pointed out that there
were significant differences in driving cognitive-motor abilities between younger and older (≥ 60 years old) age groups (e.g. Pauzie et al. 1989, Temple 1989, Waller 1991). Thus, the present study separated 32 qualified participants into two age (years) groups: younger (18–25, mean 22.3) and older (65–73, mean 67.6). Each group consisted of 16 subjects and was gender-balanced. Potential participants had to pass a health-screening test consisting of both a formal vision test (with ≥ 20/40 near and far vision) and an informal hearing test (understanding normal speech in a moving vehicle). All participants joining the present study were recruited from the Subjects’ Database of the Iowa Driving Simulator, a database of volunteers who had been solicited through the local media. All participants held a valid driver’s licence (average years as a licensed driver: younger, 3.49; older, 46.3), drove at least twice a week, 8000 km (5000 miles) per year (average estimated total km driven annually: younger, 13,960; older, 11,480), and reported as not being prone to motion sickness. None had the experience of driving simulator. Each participant was paid $10 (US) per hour for taking part in the study.

2.2. Apparatus and displays
The study used the interactive STI® low-cost, fixed-base driving simulator (developed by Systems Technology, Inc., Hawthorne, CA, USA). The STI driving simulator has been used for evaluating human driving performance and investigating medical impairment under various conditions and its validation has been testified in many studies (e.g. Stein 1990, Allen et al. 1995, Glaser and Fisher 1997). In the present study, the simulated vehicle cab, a 1993 ‘Saturn’ car, included all the normal automotive displays and controls found in an automatic vehicle. The simulator used three IBM-486 PCs to control the simulator, scenario and visual display respectively. The basic visual scenes created by the STI consisted of blue sky with two or three mountains on the horizon. The roadway was dark ash grey with yellow central lines and green verges. Street furniture consisted only of street signs, traffic lights and stop signs. The scenario graphics were projected onto a dome environment located about 4 m in front of the driver’s seat to produce 50 ×40º field of view. The steering, throttle and brake inputs were connected to the PC that controlled the STI simulator software.

A programmable and adjustable LCD (11.4 ×8.4 cm) mounted centrally above the dashboard was used as the visual display. Figure 1 depicts the LCD visual screen layout and its content descriptions are shown in table 1.

A speaker in front of the passenger seat provided ATIS auditory information in the form of a digitized human female voice with a speech rate of ~150 words/min. A speaker in the engine compartment provided driving sound effects. Hidden under the dashboard was a third speaker that provided a ‘chime’ sound as a feedback cue for the push-button tasks. Auditory information was generated by a SoundBlaster PC soundboard, and was controlled by the simulator software program. The multimodality display was a simple combination of the auditory and visual displays.

2.3. Driving loads
Two levels of low- and high-load driving conditions were defined by the parameters given in table 2. Load factors were selected based on previous research findings (Dingus et al. 1989, Noy 1989, Walker et al. 1991) and modified to be feasible for the STI simulator.
2.4. Information complexities

Information complexity for the visual display was defined in terms of the number of information units in the display. Following Labiale (1990), an information unit was used to mean the name of a geographical entity, a type of road, a position or an instruction. In this way, for example, there will be two units of information in the 65 mph (~104 km/h) speed limit sign, one for ‘speed limit’ and one for ‘65’. Miller (1956) indicated that the channel capacity of the operator is somewhere between 5 and 9 information ‘chunks’. Based on that conclusion, the simple visual display consisted of between three and five such information units, while the complex visual display presented between 9 and 14 information units. Figure 2 shows typical simple and complex visual displays designed for the present study.

Because of its serial presentation characteristics, in the auditory display modality, information complexity was defined as the frequency of presentation of information. The complex auditory display presented new information once every 5–8 s on average, compared with an interval of at least 20 s for the simple auditory display. Intervals between information presentation were kept constant as far as possible. The information content of the auditory display was equivalent to or the same as the visual display with the exception of the visual complex navigation information. It was not feasible to express the complex visual navigation information in the auditory display due to driver annoyance with the verbal equivalent of specific features. For example, the complex navigation information for the visual display contained a ‘count down bars’ and a ‘mile distance to the turn’, if one decides to make the two displays have the same information complexity, then the auditory display will annoy the drivers in a very serious way (imagine that the auditory display is always trying to inform you that you are 0.6 mile to the turn, you are 0.5 mile to the turn, ). This annoying effect was confirmed during the pilot test. The complex auditory navigation information display thus herein included the information in the equivalent visual display with the route guidance map appearing in the beginning (i.e. YOU‘RE IN FULLER AVENUE, NEXT TURN RIGHT TURN TO...
Table 1. Layout descriptions of the LCD visual display.

<table>
<thead>
<tr>
<th>LCD field</th>
<th>Information source description</th>
<th>Example(s)</th>
<th>Colour(s)</th>
<th>Complex</th>
<th>Simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation icon</td>
<td>complex route guidance&lt;sup&gt;a&lt;/sup&gt;</td>
<td><img src="image" alt="Navigation Icon" /></td>
<td>white</td>
<td>●</td>
<td>○</td>
</tr>
<tr>
<td>Icon 1</td>
<td>vehicle condition monitoring icons</td>
<td><img src="image" alt="Icon 1" /></td>
<td>red on white</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Icon 2</td>
<td>signing information icons from the ISIS and IMSIS</td>
<td><img src="image" alt="Icon 2" /></td>
<td>same as the existing signs</td>
<td>●</td>
<td>○</td>
</tr>
<tr>
<td>Icon 3</td>
<td>speed limit sign icon</td>
<td><img src="image" alt="Icon 3" /></td>
<td>black on white</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Vehicle instruments</td>
<td>turn signals</td>
<td><img src="image" alt="Vehicle Instrument" /></td>
<td>yellow</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>low/high beam signals</td>
<td><img src="image" alt="Vehicle Instrument" /></td>
<td>blue</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td></td>
<td>speedometer</td>
<td><img src="image" alt="Vehicle Instrument" /></td>
<td>white</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Text zone 1</td>
<td>turn instruction</td>
<td><img src="image" alt="Text Zone 1" /></td>
<td>TURN NEXT RIGHT</td>
<td>white</td>
<td>○</td>
</tr>
<tr>
<td>Text zone 2</td>
<td>textual information</td>
<td><img src="image" alt="Text Zone 2" /></td>
<td>HEAVY FOG AHEAD</td>
<td>red</td>
<td>○</td>
</tr>
<tr>
<td>Text zone 3</td>
<td>current street name</td>
<td><img src="image" alt="Text Zone 3" /></td>
<td>FULLER AVE.</td>
<td>●</td>
<td>○</td>
</tr>
<tr>
<td>Text zone 4</td>
<td>name</td>
<td><img src="image" alt="Text Zone 4" /></td>
<td>green</td>
<td>●</td>
<td>○</td>
</tr>
</tbody>
</table>

●, Information always appeared; ○, information sometimes appeared; ○, information never appeared. The complex/simple visual displays are described in Section 2.4.

<sup>a</sup>Information contains a picture of intersection, the distance to the turn intersection and an arrow showing which direction to turn onto. The distance to the next turn has two redundant display formats. One is a numerical distance, e.g. 0.6 mile (0.96 km), the other is a countdown bar in the form of a bar graphic. The graphic countdown bar includes a total of six bars, and each bar will disappear (countdown) in every one-sixth of the total distance to the next turn has been driven.
2.5. Scenario descriptions

The driving scenarios for the present study were developed using the STI scenario language (SDL v.6.0). Each participant completed a 4-mile practice scenario before completing six experimental driving scenarios with visual-only, auditory-only or multimodality display of information under high- or low-load driving conditions. Each scenario lasted ~10 min and consisted of two sessions of ~5 min each with presentation of simple and then complex information, or vice versa. Participants were told to bring the car to a complete stop after the first session, to switch complexity of information, and were allowed a short rest between scenarios.

2.6. Tasks

To establish measures of drivers’ behaviours with differing ATIS information (i.e. IRANS, ISIS, IVSAWS), each participant was required to perform three tasks concurrently:

1. Driving task. All participants were requested to complete the simulated driving course as fast as possible while following all traffic rules (signing information). Participants were asked to make as few mistakes as possible.

2. Navigation task. Owing to limitations in the STI simulator, participants did not make turns for those route guidance directions shown on the displays.

<table>
<thead>
<tr>
<th>Driving load factors</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane width (m)</td>
<td>3.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Road type</td>
<td>almost straight multilane</td>
<td>curvy two way</td>
</tr>
<tr>
<td>Number of easy curves</td>
<td>–</td>
<td>eight (3100 m in radius)</td>
</tr>
<tr>
<td>Number of sharp curves</td>
<td>two (1500 m radius)</td>
<td>four (310 m radius)</td>
</tr>
<tr>
<td>Speed limits (km/h)</td>
<td>72 in general</td>
<td>96 in general</td>
</tr>
<tr>
<td></td>
<td>56 in sharp curve</td>
<td>64 in sharp curve</td>
</tr>
<tr>
<td></td>
<td>40 in road construction</td>
<td>56 in road construction</td>
</tr>
<tr>
<td>Traffic density(a)</td>
<td>light</td>
<td>heavy</td>
</tr>
<tr>
<td></td>
<td>(eight vehicles in average)</td>
<td>(80 vehicles in average)</td>
</tr>
<tr>
<td>Number of intersections</td>
<td>17 in average</td>
<td>50 in average</td>
</tr>
</tbody>
</table>

\(a\)Total number of oncoming vehicles in the opposite lane.

\(b\)Road construction in this study created two task situations, one for the road condition monitoring responses (the push button task), the other to inform the drivers (~3.5 s after presenting the road warning information) the speed limits requirements (the driving task).
Instead, participants were instructed to behave as if they were about to turn, i.e. slow down and turn on the turn signal as they approached the turn street, and then verbally informed the experimenter as to which direction (i.e. left or right) they intended to turn and also, if possible, the name of the street onto which they were turning. On receipt of this verbal information, the experimenter would then instruct participants to continue driving straight along the original road at normal speed. There was a total of eight ‘turns’ for each display modality (four ‘turns’ in each scenario).

(3) Push-button task. In the visual display modality, the push-button task included both the detection and the identification of vehicle condition
information icons (e.g. high engine temperature, low oil pressure) and textual information on road condition (e.g. heavy fog ahead, road construction ahead). This information was presented for 3 s. Push-button tasks were the same for the auditory display modality except that all information was presented verbally. A semantic alerting cue—warning—preceded the warning messages, e.g. Warning! High engine temperature. For the multimodality display, the warning information was presented on both visual/auditory displays redundantly.

Participants were instructed to respond as fast as possible to warning information by pushing one of two buttons on the steering wheel, the left one for ‘road conditions’, the right one for ‘vehicle conditions’. Each scenario contained eight push-button tasks.

2.7. Experimental designs
This study was a 2 × 3 × 2 × 2 mixed-factors model that compared results by age (two levels, between-subjects), display modality (three levels, within-subject), driving load (two levels, within-subject) and information complexity (two levels, within-subject). Variables were assigned to participants randomly but were counterbalanced to prevent any learning/order effect. Dependent variables were based on both objective and subjective measures, and are described below.

2.7.1. Objective measures: The objective measures obtained from the three task performances were:

1. Response time. Elapsed time between the presentation of information on the display (for the auditory display, this was measured from the beginning of the verbal warning) and pushing the correct button.
2. Number of missed button pushes. More missed button pushes suggest that the participants had more difficulty in detecting the presented information.
3. Total number of correct turns. The number of correct turns is a content-valid measure of the driver’s ability to perform the navigation task under different conditions.
4. Navigation-related errors. (i) Number of near miss turns: participants who did not slow their vehicle when approaching the turn but did respond verbally and correctly. Also, participants who drove through the turn street and then remarked that they had just missed a turn and identified the turn correctly. (ii) Number of missed turns: turns where there was no verbal response from the participant. (iii) Number of wrong turns: participant indicated the wrong turn direction or gave the wrong street name.
5. Mean velocity. Average vehicle speed is a somewhat face-valid measure of task demands (Antin et al. 1990).
6. Mean absolute velocity deviation. Monty (1984) found that the speed maintenance to be a sensitive index in measuring the amount of attention demanded by the secondary tasks. The mean absolute deviation from the speed limit is the measure for determining performance in this speed maintenance task. Larger differences indicate the participant was either unaware of the speed limit presented on the displays, had difficulty in maintaining the speed requirement due to other task demands, or both.
Variance in lateral acceleration. Abrupt lateral manoeuvres are indicative of a vehicle that has come off lane centre track due to driver inattention (Dingus et al. 1997).

Variance in steering wheel position. Changes in driver steering behaviour occur with changes in driver attention (McDonald and Hoffmann 1980). Since variance is decreased by small corrections and increased by large ones, an increase in the steering wheel position variance indicates a reduction in driving performance and suggests high workload requirements.

Variance in lateral lane position. The lateral lane position is the position of the vehicle centre with respect to the road’s central dividing line.

Frequency of major lane deviation. These occurred when the vehicle’s centre point crossed either the central line or the road boundary. This and preceding measure provide valuable face-valid measures of driving task interference resulting in performance degradation.

2.7.2. Subjective measures: Subjective measures were obtained using a modified three-point scale (low, 1; medium, 2; high, 3) SWAT workload assessment (Reid and Nygren 1988) and a Likert seven-point preference rating system (from 1, ‘dislike it very much’, to 7, ‘like it very much’). Detailed individual dimensions of SWAT were: (1) time stress: amount of time available for completion of the driving and navigation tasks; (2) visual effort: amount of visual scanning required; (3) psychological stress: feelings of confusion, frustration, danger and anxiety; and (4) overall workload: combination of all of the three subjective workload ratings.

2.8. Data collection
The experimenter used a turn check sheet to record the turn direction, turn street name and navigation-related errors. All objective data were recorded automatically by the STI simulator in every 3.048 m (10 feet). The SWAT and preference measures were taken at the end of each segment, i.e. at the midpoint and at the end of each scenario.

2.9. Procedures
Before participating in the experiment, participants were prescreened to ensure that they were currently licensed drivers, met the age requirement and could pass a vision and hearing test. Eligible participants were asked to read information summary that addressed the purpose of this experiment, and then to watch a training video of ~15 min. The training video consisted of three parts. The first described the three display modalities used in presenting different information. Each simulated system was explained, and any questions the participants had were answered. The second part briefly depicted the scenario scenes and the STI simulator as they would be used during the experiment. The third part explained the tasks and how to perform them. After watching video, the three definitions of the SWAT workload scale and what was required to perform the push-button tasks were read to the participants again to make sure they clearly understood them and kept them in mind. Finally, the participants signed an informed consent form and left the briefing room to go to the STI simulator room.

The experimenter informed the participants that their first priority was to drive the simulator under normal circumstances, once they felt comfortable sitting in it. Then the participants were given a practice run in the simulator. While driving the
practice course, participants were trained to adjust/use the different displays. The practice course continued until the participants drove through selected tasks without errors. At the end of the practice session, a SWAT workload evaluation was performed to ensure that the participants experienced the situation, and to have the experimenter ensure they understood the definitions appropriately.

After completion of the practice run, data collection began. The participants performed the three tasks mentioned above over six scenarios. A short break was taken if necessary after each scenario trial. It took 90 min for younger participants to complete the present study, while for older participants, 2 h total was required.

3. Results

Data collected for the present study were analysed by inferential statistics of ANOVA/MANOVA. The Student-Newman-Keuls (SNK) and treatment contrast tests were used for post-hoc comparisons. Data obtained from the navigation-related errors, however, due to very small number values within each data cell, were only described. The results described here should be interpreted by looking for supporting evidence across all of the performance measures collected.

3.1. Age effect

Age was statistically significant in push-button performance, navigation performance, subjective workload ratings and driving performance. Table 3 summarizes the applicable results. Overall, the older drivers performed worse than the younger drivers.

In the push-button task, significant interactions between age and display modality were found for the response times \( F(2,60) = 9.87, p = 0.0002 \) and the number of missed button pushes \( F(2,60) = 14.6, p = 0.0001 \).

As table 4 shows, older participants using the visual display had slower response times and a greater number of missed button pushes. The multimodality display reduced the number of misses for both groups, but this improvement was especially significant for the older drivers.

Among the driving performance measures, only the variance of steering wheel position was significantly different between the age groups and the display modalities \( F(2,60) = 3.1, p = 0.0494 \). The contrast tests revealed that the older group had the

<table>
<thead>
<tr>
<th>Performance measures</th>
<th>Younger</th>
<th>Older</th>
<th>( F(1,30) )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean response times (s)</td>
<td>2.75</td>
<td>3.81</td>
<td>12.64</td>
<td>0.0013</td>
</tr>
<tr>
<td>Total correct turns (%)</td>
<td>97.92</td>
<td>92.19</td>
<td>15.25</td>
<td>0.0005</td>
</tr>
<tr>
<td>Numbers of navigation-related errors(^a)</td>
<td>12</td>
<td>45</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mean time stress ratings</td>
<td>1.47</td>
<td>1.91</td>
<td>9.82</td>
<td>0.0038</td>
</tr>
<tr>
<td>Mean psychological stress ratings</td>
<td>1.52</td>
<td>1.92</td>
<td>6.93</td>
<td>0.0133</td>
</tr>
<tr>
<td>Mean velocity (m/s) — high/low driving load conditions</td>
<td>19.88/ 18.27/</td>
<td>7.89/ 7.89/</td>
<td>0.0087/</td>
<td></td>
</tr>
<tr>
<td>Mean absolute velocity deviation (m/s) — high driving load only</td>
<td>16.33</td>
<td>15.03</td>
<td>5.45</td>
<td>0.0264</td>
</tr>
<tr>
<td>Variance of steering wheel position (radians) — high driving load only</td>
<td>4.31</td>
<td>4.85</td>
<td>21.51</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>0.0093</td>
<td>0.022</td>
<td>23.36</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

\(^a\)Descriptive statistics only.
largest steering wheel angle variance when using the visual display \( F(1,90)=6.03, p=0.0160 \) for auditory versus visual; \( F(1,90)=10.40, p=0.0018 \) for visual versus multimodality], while the difference between the auditory display and the multimodality display was not statistically significant. The younger group showed no differences between the three display modalities in this measure.

The following results highlight effects of the three display modalities, information complexities and driving load conditions on the three task performances.

### 3.2. Response times and number of missed button pushes

In the response time measures, the interaction between display modality and information complexity \( F(2,60)=14.61, p=0.0001 \) was significant. Post-hoc analysis revealed that a slower response time for the visual modality under the complex information condition was statistically significant \( F(1,186)=22.29, p=0.0001 \) for auditory versus visual; \( F(1,186)=35.02, p=0.0001 \) for visual versus multimodality; \( F(1,186)=1.48, p=0.2259 \) for auditory versus multimodality. Results are summarized in Table 5.

Similar results were also found for the number of missed button pushes. Overall, users of the multimodality display produced fewer misses (29) than those of the auditory condition (75) or the visual condition (110) \( F(2, 60)=31.32, p=0.0001 \).

### 3.3. Total number of correct turns

Significant differences were found in the high driving load condition. The visual display showed the lowest percentage (90.63%) of correct turns \( F(1,186)=5.12, p=0.0248 \) for auditory versus visual; \( F(1,186)=9.68, p=0.0022 \) for visual versus multimodality. The difference between the auditory display (96.88%) and the multimodality display (99.22%) was not significant. Under the low driving load condition, no significant differences were found.

### 3.4. Navigation-related errors

As Table 5 shows, the auditory display accounted for the largest number of wrong turns, 14 of 19 recorded, all of which occurred in the complex information condition. The visual display accounted for the largest number of missed turns, 13 of 27 recorded. With the multimodality display, there were very few navigation-related errors (four times for near miss, five times for miss, four times for wrong turns). For complex information, there was a significant reduction of navigation-related errors.
Table 5. Performance data broken down by information complexity and display modality.a

<table>
<thead>
<tr>
<th>Performance measures</th>
<th>Simple information</th>
<th>Complex information</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Auditory</td>
<td>Visual</td>
</tr>
<tr>
<td>Response times (s)</td>
<td>2.687 A</td>
<td>3.255 A</td>
</tr>
<tr>
<td>Number of missed button pushes</td>
<td>24 A</td>
<td>30 A</td>
</tr>
<tr>
<td>Navigation-related errorsb</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Near misses</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Misses</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Wrong turns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High driving load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variance in lateral acceleration (m/s²)</td>
<td>0.042 A</td>
<td>0.043 A</td>
</tr>
<tr>
<td>Variance in lateral lane position (m)</td>
<td>0.421 A</td>
<td>0.442 A</td>
</tr>
<tr>
<td>Variance in steering wheel position (radians)</td>
<td>0.018 AB</td>
<td>0.0122 B</td>
</tr>
<tr>
<td>Low driving load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variance in steering wheel position (radians)</td>
<td>0.07 A</td>
<td>0.077 A</td>
</tr>
<tr>
<td>Mean absolute velocity deviations (m/s)</td>
<td>3.14 A</td>
<td>3.47 A</td>
</tr>
</tbody>
</table>

a Data on the same line within each information complexity labelled with the same letter were not significantly different (x = 0.05).
b Descriptive statistics only.

with the multimodality display. Surprisingly, using the complex information visual display produced zero wrong turn error, and its only one wrong turn error was in the simple information condition. Unexpectedly, in the simple information condition, most of the navigation-related errors with the multimodality display were found in the low driving load condition (eight out of nine recorded; the only one wrong turn occurred in the high driving load condition).

3.5. Driving performance

The driving performance data were separated into two subsets according to driving load conditions, for easiness of reading.

Under the high driving load condition, participants tended to drive faster when using the auditory display (mean velocity 19.55 m/s) [F(2,60) = 4.07, p = 0.0021] than when using either of the other two displays (mean velocity, visual 18.75 m/s, multimodality 18.82 m/s). Mean absolute velocity deviations were much lower with the multimodality display (mean deviation from speed limits, multimodality 3.99 m/s, visual 4.85 m/s, auditory 4.93 m/s) [F(2,60) = 21.31, p = 0.0001]. The higher mean deviations with the visual and auditory displays resulted from the participants driving more slowly and faster respectively. The visual display also resulted in
significantly greater variance in lateral acceleration \( [F(2,60) = 3.86, \ p = 0.0266] \), variance in lateral lane position \( [F(2,60) = 5.76, \ p = 0.0051] \) and variance in steering wheel position \( [F = (2,60) = 4.18, \ p = 0.0199] \). A significant interaction was found between display modality and information complexity \( [F(2,60) = 3.19, \ p = 0.048] \) in the variance of lateral acceleration. The lateral acceleration variance was greatest when using the visual display under the complex information condition (table 5), and the difference between the auditory display and the multimodality display in that condition was not statistically significant \( [F(1,186) = 0.21, \ p = 0.6469 \) for auditory versus multimodality]. No statistical differences were found when using the three different displays in the simple information condition.

The variances in lateral lane position and in steering wheel position, and the frequency of major lane deviations also varied significantly with information condition and display type \( [F(2,60) = 6.75, \ p = 0.0023, \ F(2,60) = 9.63, \ p = 0.0002, \ F(2,60) = 22.09, \ p = 0.0001 \) respectively]. Visually presented complex information made drivers difficult in controlling their vehicle properly and led to more frequent major lane deviations than when such information was presented by the other two displays (table 5). All of this evidence suggests that, at least under high driving load condition, the visual modality requires more driver attention and leads to less safe driving behaviour than the other two modalities.

Similar results were also found in the low driving load condition. Participants using the visual display had the largest mean absolute velocity deviation \( [F(2,60) = 10.69, \ p = 0.0001] \), and, unexpectedly, participants made the largest number of major lane deviations in the multimodality display condition (auditory 16, visual 17, multimodality 31) \( [F(2,60) = 3.92, \ p = 0.0251] \). In addition to the main effect, two significant interactions were found between information complexity and display modality for variance in steering wheel position \( [F(2,57) = 3.56, \ p = 0.0351] \) and variance for the mean absolute velocity deviations \( [F(2,57) = 9.36, \ p = 0.0003] \) (table 5). Complex information presented on the visual display resulted in significantly greater variance in steering wheel position than when the same data were presented on the multimodality display \( [F(1,183) = 4.67, \ p = 0.0320 \) for visual versus multimodality; \( F(1,183) = 3.70, \ p = 0.0559 \) for auditory versus multimodality].

3.6. Subjective workload and preference

For both the complex information and high driving load conditions, all participants without exception reported more time stress, visual effort and combined workload than for the simple information and the low driving load conditions. Participants also disliked receiving complex information in all three display modalities \( [F(1,30) = 7.62, \ p = 0.0097] \).

A two-factor interaction, modality × driving load, was significant in the time stress ratings \( [F(2,60) = 4.51, \ p = 0.0149] \). Significant differences were found in the high driving load condition: the visual display received a higher time stress rating (1.97) than did the auditory display (1.66) \( [F(1,186) = 4.11, \ p = 0.0442] \), but the visual display rating did not significantly differ from that of the multimodality display (1.67) \( [F(1,186) = 3.70, \ p = 0.0558] \).

The three displays also significantly differed in terms of the visual effort \( [F(2,60) = 15.45, \ p = 0.0001] \), psychological stress \( [F(2,60) = 4.68, \ p = 0.0129] \), combined workload \( [F = (2,60) = 7.44, \ p = 0.0013] \) and preference ratings \( [F = (2,60) = 15.47, \ p = 0.0001] \). Table 6 summarizes these results.
4. Discussion and conclusions

4.1. Effect of age on performance

Driver age is an important consideration in the design of ATIS displays not least because the number of older drivers continues to increase. Studies showed that older drivers experience more attention demands (Dingus et al. 1997) and have poorer perceptual/cognitive abilities (Temple 1989). The experimental results reported here are consistent with these earlier studies in that older participants had slower response times, missed more button pushes, made fewer correct turns and more navigation-related errors, reported higher time stress, psychological stress and overall workload, and they also drove slowly and controlled their vehicles relatively poorly. Their performance also degraded more than the younger participants in the high driving load condition. Older drivers also performed worse with complex information than with simple information, although this was true for both age groups. All of this suggests that for older drivers especially, ATIS user interfaces should be designed in ways that do not increase the drivers workload, and that information should be kept as simple as possible.

In general, since both age groups performed better with the multimodality display, and improvement was especially noticeable for the older drivers in, for instance, the push-button tasks results (table 4). The presentation of information on a multimodality display appears to go some way toward fulfilling these criteria.

Older participants tended to drive slowly and cautiously, especially when using the visual display. This is presumably to compensate for the higher driving workload. Larger variance in the steering wheel position also suggested that the older drivers experienced higher driving attention demands while driving, and again, this is consistent with the overall cautious/conservative driving pattern that was observed in the older drivers. By contrast, the younger participants who reported a low mental workload and may have low risk perception tended to drive faster especially when using the auditory display.

4.2. Overall performance and preferences for display modalities

The author hypothesizes that better results were obtained with the multimodality display (tables 5 and 6) because it made smaller attention demands than either of the single display modalities. Workload and preference ratings, which further suggest that the participants preferred to use the multimodality display, appear to support this hypothesis.

With the multimodality display, participants adhered more closely to the speed limits and thus produced the smallest mean absolute velocity deviation. This result

<table>
<thead>
<tr>
<th>Subjective rating</th>
<th>Auditory</th>
<th>Visual</th>
<th>Multimodality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time stress — high driving load</td>
<td>1.66 B</td>
<td>1.97 A</td>
<td>1.67 AB</td>
</tr>
<tr>
<td>Visual effort</td>
<td>1.65 B</td>
<td>2.13 A</td>
<td>1.70 B</td>
</tr>
<tr>
<td>Psychological stress</td>
<td>1.68 B</td>
<td>1.84 A</td>
<td>1.63 C</td>
</tr>
<tr>
<td>Combined workload</td>
<td>5.00 B</td>
<td>5.73 A</td>
<td>4.96 B</td>
</tr>
<tr>
<td>Preference</td>
<td>4.75 B</td>
<td>4.21 C</td>
<td>5.21 A</td>
</tr>
</tbody>
</table>

*Means with the same letter were not significantly different (α = 0.05).
suggests that this display, to some extent, may also be good at helping drivers follow other regulatory signing information.

Driving performance was the least affected by the multimodality display, and therefore imposed the least additional demands on attention. The relevant measure results include variance in lateral acceleration, frequency in major lane deviations (table 5), variance in lateral lane position, and variance in steering wheel position. Together with the subjective workload results (table 6), this further suggests that under high driving load, complex information conditions, the multimodality display imposes the least in attentional demands on attention. These good performance results confirm the multiple resource theory prediction that proposes that different modalities represent separate attentional resources and thus should lead to improved task-sharing performance. Again, this argues for a multimodality ATIS user interface.

In general, as noted above, the multimodality display produced lower workload and stress ratings. In the time stress rating, however, although the multimodality display rating was lower than the visual modality rating, these two values were not significantly different (table 6). It is presumably because the multimodality display includes both the visual and auditory channels, participants may have tendency to see the visual display to re-confirm visually data that are received via the audio channel and thus partially increase the time stress involved. Two unexpected results occurred in the low driving load condition with the multimodality display were the large navigation-related errors and high frequency of major lane deviations. These results might have been caused by an inverted ‘U’ performance-anxiety phenomenon. Once the drivers had got used to the multimodality display and felt comfortable/confident, they may begin to feel relaxed and complacent or even depend mainly on one of the modalities. This may encourage them to perceive very little risk and thus drive recklessly in this low driving condition. A future study may therefore also consider including a design feature that allows drivers or systems to turn off either mode of the multimodality display either manually or else based on driving load conditions. In any case, more work will be needed to investigate these possibilities.

Auditory displays have received lower workload ratings (Labiale 1990) and are suitable for presenting warning information because of the fast response they elicit from the drivers/operators (Sorkin 1987). Similar results were found in the present study. However, results from the measures of the number of missed button pushes, the navigation-related wrong turn errors, and the absolute mean velocity deviation data all suggest that drivers may have difficulty in paying attention to the auditory display all the time. When driving conditions and information are complicated, drivers may have more difficulty in filtering and remembering useful information presented by an auditory display because of the memory interference problem. In any case, auditory information items evidently need to be carefully organized. Repetition of aural safety-related information on the auditory display may also be advisable. On the other hand, listening to the radio is a common activity for most drivers. System designers should take this into account as well. A design feature of ‘insert’ function borrowed from the so-called in-vehicle audio phone system may be feasible for solving this problem.

In the present study, although drivers using the visual display performed worse in most task measures and subjective ratings, and presentation of complex information led to the worst performance, the complex visual navigation configurations
compatible with the road environment used here nonetheless resulted in the fewest wrong turn errors. A trade-off therefore still exists between the two objectives of driving safely and perceiving/detecting the information correctly on the visual display.

Future studies might usefully investigate whether or not long term use of the three display modalities leads to changes in performance, preferences and/or the safety/information trade-off.

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References


