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Interference With Driving or In-Vehicle Task Information: The Effects of Auditory Versus Visual Delivery

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ABSTRACT

Eighteen published studies were identified in the literature in which auditory versus visual delivery of in-vehicle task information was contrasted in relatively realistic driving simulations (or on-the-road evaluations). An annotated bibliography of these studies is provided in the appendix. In synthesizing the collective results of these studies, we find that a majority point to the advantage for auditory delivery in both primary (driving) and secondary (in-vehicle) task performance. Factors are identified that modulate this advantage, such as workload, the location of the visual display (HUD vs. head down) and the relatedness of the in-vehicle task to the driving task. In particular, increases in in-vehicle task load lead to a more selective loss for in-vehicle task performance when it is delivered auditorally. In contrast, greater benefits of auditory delivery appear when the in-vehicle task is related to the driving task.

1. OVERVIEW

Driving is a multitask environment which requires concurrent processing. The primary task of the driver is to simultaneously guide the position of the vehicle, detect and classify potential hazards, and to navigate the route. Secondary tasks compete for resources and may, under some conditions, degrade the primary driving performance. Our review of the literature, included in the appendix to this report, has focused on those secondary tasks imposed by in-vehicle technology (IVT), and the extent to which changes in the display of IVT can influence the competition for the visual, cognitive and motor resources necessary for the primary driving tasks of vehicle control and hazard detection. The specific target of our review is on the switch in modality of IVT display from visual to auditory, when the visual display is presented in either a head up or head down location. Within the context of a multiple resource model of processing resources (Wickens, 2002; Horrey & Wickens, 2002), the change (visual → auditory) is said to avail separate resources not used in the primary tasks of driving. In addition to evaluating the modality display changes, we also consider how the costs or benefits of this change are affected by three secondary factors, the location of the visual display, the extent to which the IVT is relevant to driving (as in ATIS information) or is irrelevant (as in displays for “infotainment”), and the level of workload imposed by the primary and secondary tasks. As we have noted above, each study was classified in terms of whether a change of IVT display from visual to auditory improved dual task performance (A>V), left that performance unchanged (A=V) or actually disrupted that performance (A<V). This trichotomy of display change effects was imposed on both the primary (driving) and secondary (IVT) task performance.

2. SYNTHESIS OF LITERATURE

The literature review presented in the appendix of this report is organized according to the effects of auditory and visual presentation of in-vehicle tasks on primary and secondary task performance. The results are summarized in Table 1, and the categories of the table represent whether an auditory cost (“V > A”) or auditory benefit (“A > V”) is seen with respect to the primary driving task and the secondary in-vehicle task. An auditory cost translates to better performance (primary and secondary task measures) using the visual modality to present information as opposed to the auditory modality; an auditory benefit translates to better performance (primary and secondary task measures) using the auditory modality to present information as opposed to the visual modality. Each study included in the literature review table is summarized according to the following four categories: 1) a description of the secondary in-vehicle technology (IVT) task; 2) a description of the primary driving task; 3) the results of modality manipulation on the primary driving task; and 4) the results of modality manipulation on the secondary IVT task.

The 18 total studies are organized under the following 9 subtitles:

I. Primary task: A > V; Secondary task: A > V
II. Primary Task: A > V; Secondary Task: V > A
III. Primary Task: A > V; Secondary Task: A = V
IV. Primary Task: A = V; Secondary Task: A > V
V. Primary Task: A = V; Secondary Task: V > A
VI. Primary Task: A = V; Secondary Task: A = V
VII. Primary Task: V > A; Secondary Task: A > V
VIII. Primary Task: V > A; Secondary Task: V > A
IX. Primary Task: V > A; Secondary Task: A = V

Table 1 summarizes the 18 studies according to their subtitle categories:

Table 1.

	Secondary Task		
Primary Task	***A > V***	***A = V***	***V > A***
A > V	1) Burnett, G.E., & Joyner, S.M. (1997) 2) Dingus, T.A., Hulse, M.C, McGehee, D.V., & Manakkal, R. (1994) 3) Gish, K.W., Staplin, L., Stewart, J., & Perel, M. (1999) 4) Liu, Y-C. (2001) 5) Srinivasan, R., Yang, C., Jovanis, P., Kitamura, R., & Anwar, M. (1994) 6) Streeter, L.A., Vitello, D., & Wonsiexicz, S.A. (1985) 7) Walker, J., Alicandri, E., Sedney, C., & Roberts, K. (1990)	1) Hurwitz, J., & Wheatley, D.J. (2002) 2) Ranney, T.A, Harbluk, J.L., & Noy, Y.I. (2002) 3) Srinivasan, R., Jovanis, P. (1997)	1) Labiale, G. (1990)
A = V	1) Parkes, A.M., & Burnett, G.E. (1993)	1) Dingus, T.A., McGehee, D.V., Manakkal, N., Jahns, S.K., Carney, C., & Hankey, J.M. (1997)	1) Lee, J.D., Gore, B.F., Campbell, J.L. (1999)
V > A	1) **Lee, J.S. (1997) 2) Mollenhauer, M.A, Lee, J., Cho, K., Hulse, M.C., & Dingus, T.A. (1994)	1) Horrey, W.J., & Wickens, C.D. (2002)	1) Matthews, G., Sparkes, T., & Bygrave, H. (1996)

****** Not included in detailed bibliographic review.

In the following sections, we integrate and synthesize the general characteristics of different studies that associate them with a particular region of the table. In making this association, it is important to note that different investigators used various means of assessing driving “performance”. Some, such as lane keeping, may be highly sensitive; others such as total driving time may be much less so. Hence, it is possible that differences in studies where effects have and have not been found might be related to insensitivity of performance measures in the latter case, rather than to fundamental contradictions in results.

2.1 In-Vehicle Tasks (Relevant vs. Non-relevant)

The majority (13/18) of vehicle-based AV studies analyzed in the table above, have delivered related (ATIS, Navigation) information, rather than unrelated IVT information. Of these 13, nine revealed that auditory presentation of side task information provided less disruption of driving than visual presentation of side task information (“A>V”), three revealed that auditory and visual presentation of side task information yielded equivalent effects on driving performance (“A=V”), (Parks & Burnett, 1993; Lee et al., 1999; Dingus et al., 1997), and one revealed that visual presentation of side task information resulted in less distraction to driving performance than auditory presentation of side task information (“V>A”; Mollenhauer et al., 1994).

In contrast to the above, an auditory cost is more likely to be seen in studies that utilize secondary tasks that carry less direct relevance to the driving task. As an example, a study by Matthews, Sparkes, and Bygrave (1996), required participants to perform Baddeley’s (1968) Reasoning Test as a secondary task to the primary driving task. Subjects were asked to judge whether simple sentences followed by a letter pair were true or false. The task had no bearing on the nature of the driving task and participants were unable to integrate secondary task information to assist in the tasks involved in driving. Results yielded a cost of utilizing the auditory modality for presentation of the varying sentences; a dual-task inference was found only in curve driving in the auditory condition with no incidence of dual-task inference found in the visual condition. The study by Horrey and Wickens (2002) additionally reported a slight cost of presenting unrelated auditory information with the auditory condition exhibiting more variation in speed control relative to the head-down visual condition. Indeed, of the 4 studies that employed non-relevant secondary task information, 2 of the studies (Hurwitz &Wheatley, 2002; Ranney et al., 2002) showed an auditory benefit in presenting non-relevant secondary task information, representing a considerably smaller proportion (2/4 = 50%) than those showing auditory benefits with related tasks (9/13 = 70%). Furthermore, while only 1/13 studies (8%) with related information showed an auditory cost, 2/4 (50%) of the studies with unrelated information showed an auditory cost.

While this difference in percentage is not statistically significant, given the very small sample of driving-irrelevant task studies, it does suggest a trend, that is partially supported by other data, suggesting that irrelevant auditory messages can be distracting from primary visual tasks (e.g., Latorella, 1998; Wickens & Liu, 1988). A non-driving study by Tsang and Rothschild (1985) that employed a non-relevant secondary task presented a spatial transformation task in conjunction with a compensatory tracking task supports this interpretation. The results indicated a cost to presenting the spatial information aurally (achieved through variance of tone location) as opposed to presenting the information visually. Participants are distracted by the information as opposed to being assisting in performing the driving task. Because irrelevant tasks do not support the task of driving, a primarily visual task, there is no benefit in offloading cognitive demands to the auditory modality in decreasing the workload of the driving task.

Thus a case can be made that irrelevant visual information does not distract drivers to the same degree as irrelevant auditory information because of the cognitive mappings of the driving task as primarily requiring integration of multiple sources of visual information. The schema of driving would render expectations of utilizing visual resources for a wide variety of tasks. Drivers are therefore apt at integrating pertinent visual information and additionally at filtering out irrelevant visual information relative to the driving task. Drivers are however less skilled in being able to integrate (or filter) irrelevant auditory information when they are concurrently performing the visual driving task, and indeed such auditory delivery has been found to "preempt" ongoing visual tasks in aviation research (e.g., Helleberg & Wickens, 2002; Latorella, 1998).

Wickens and Liu (1988) developed a "signature" of this auditory preemption effect, whereby a discrete secondary task (here represented by the IVT) benefits from auditory delivery of its own information, since that delivery will "call attention" to its message, whereas the ongoing visual task (here, driving) will suffer by auditory relative to visual delivery of the secondary task, as attention is discretely switched away from driving by the intrusive auditory onset. Studies showing the strongest form of this effect would be those contained in the lower left cell of table 1 (two studies), whereas those showing a weaker form, where either the primary or secondary task was unaffected by the modality switch, are those shown in the left-middle (1 study) or center bottom (1 study) cells of the table.

Finally, while the auditory-visual / related-unrelated interaction can be tied with auditory preemption of unrelated task, it is important to note that this can also be linked to emerging findings from the field of educational technology, in which the **cognitive load theory** articulated by Sweller and his colleagues (e.g., Tindall-Ford et al., 1997; see Wickens & Hollands, 2000, chapter 6 for a summary). Proponents of this theory stress that when delivering related verbal and spatial (i.e., pictorial) information for instruction, the former is more effectively delivered by speech (auditory) than by text (visual).

2.2 Display Separation

A major feature of many of the "relevant" studies that were surveyed was a large visual separation either downward, and or rightward from the drivers' forward line of sight. In the majority of the studies (12/13), this separation appeared to be greater than 20 degrees. Of the 12 relevant studies that utilized visual displays with greater than 20 degrees separation, all but three (Dingus et al., 1997; Parks & Burnett, 1993; Lee et al., 1999) appeared to show a clear advantage of auditory displays over visual displays in terms of their effects on the primary task. Of these three exceptions to the visual cost, Dingus (1997) used a somewhat different IVT (hazard alert), and Parks and Burnett (1993) appeared to only use "driving time" as a primary task driving measure (i.e., no measure of driving safety); these three studies reported ambiguous (equivalent auditory and visual displays) results no matter whether the visual condition was minimally or maximally separated.

In contrast, of the five studies that appeared to have a separation angle of less than 11 degrees, one revealed an advantage of auditory over visual display use (Burnett & Joyner, 1997), two revealed equivalent results with the auditory and visual display use (Horrey & Wickens 2002 - with the HUD, Srinivasan et al., 1997 – with the HUD), while two actually found an advantage of using a visual display over an auditory display (Mollenhauer et al., 1994; Matthews et al., 1996). Note that Matthews (1996) was a study in which the IVT display was **unrelated** to driving. Thus it appears that when there is substantial visual display separation (>15 degrees), there is usually a cost to using the visual display over the auditory display. When there is not a large display separation, the results are equivocal, showing either no difference, or a visual advantage. These 4 equivocal results are equally divided between driving-related IVTs and unrelated IVTs. Of the 4 equivocal results, only two (Horrey & Wickens, 2002, Srinivasan et al., 1997) examined driver response to unexpected hazards to be discussed in more detail in the following section. Thus it appears in summary that HUD presentation can mitigate most if not all of the costs of visual-visual interference and, in some conditions, restore dual task performance to a level that is equivalent, if not sometimes superior to, auditory display conditions.

2.3 Hazard Event Detection

The majority of studies examined driving performance primarily in terms of the continuous measures such as lane keeping, or speed and headway control. Of the 17 total studies reviewed, only five (Gish et al., 1999; Horrey & Wickens, 2002; Ranney, Harbluk, & Noy, 2002; Srinivasan et al., 1994; Srinivasan, 1997) examined hazard RT (as opposed to other aspects of primary task driving performance). Gish et al. (1999) found that auditory presentation of secondary task information results in faster and more accurate detection of roadway hazards than did visual head down presentation of secondary task information. Ranney et al. (2002) found similar results when hazard detection was simulated by requiring detection of peripheral visual events. Horrey and Wickens (2002) found that auditory presentation of secondary task information yielded better hazard detection than visual presentation if the visual display was head-down, but that there were no modality differences if the visual display was head-up. Srinivasan et al. (1994, 1997) provided a somewhat confusing and mixed set of results, but these appear to suggest that auditory presentation is equivalent to visual presentation both when the visual display is head up AND when the visual display is head down. Thus the data provide modest, but not conclusive evidence that there is a benefit for auditory over visual presentation of IVT information in the detection of unexpected visual events, a benefit which, like that of lane keeping, will grow if the visual IVT display is head down.

2.4 Workload

Primary Task Workload

Only six studies apparently looked systematically at how any performance difference in auditory versus visual information displays were modified by driving workload or driving task complexity (i.e., in terms of a modality x complexity interaction in some measure of driving performance; Liu, 2001; Walker et al., 1990; Hurwitz & Wheatley, 2002; Srinivasan & Jovanis, 1997; Horrey & Wickens, 2002; Matthews, Sparkes, & Bygrave, 1996). Two additional studies (Srinivasan et al., 1994; Streeter et al., 1985) did vary road type complexity in their driving environments but did not parse out the effects of the differing road types to examine workload interactions. Of the six studies that did investigate workload effects, three studies found an auditory benefit on driving performance (Liu, 2001; Hurwitz & Wheatley, 2002; Srinivasan & Jovanis, 1997). Liu (2001) found that an auditory benefit for mean speed (faster speed) was amplified at higher levels of driving workload, but that an auditory benefit for speed variability (lower variability) was not modulated by higher driving load. In interpreting these results, it should be noted that higher speed does not necessarily translate to better driving performance. Hurwitz and Wheatley (2002) found that the benefit to driving performance of auditory displays over visual displays increased as the driving load increased from a straight track to a curved track. Srinivasan and Jovanis (1997) reported that an overall driving benefit associated with auditory deliver, increased with the more complex driving situations. Walker et al., did not report data to allow the inference as to how workload influenced the effect of display modality on driving performance (i.e., the workload x modality interaction).

In contrast to the above examples, Horrey and Wickens (2002) found no interaction between increased driving load (road curvature and urban driving environment) and display modality. Only one study showed a clear auditory cost to the driving task in increasing workload (Matthews, Sparkes, & Bygrave, 1996). Matthews et al. (1996) found that dual-task interference was evident only in curve driving in the auditory condition; a finding that did not occur in straight driving, inferring that increasing driving load creates an auditory cost. As noted previously, the tasks used by both Horrey and Wickens and by Matthews et al. were non-relevant to the driving task.

In some studies, the manipulation of driving load affected the IVT performance. Liu (2001) found that an increase in driving load led to improved navigation using an auditory display compared to using a visual display (with the highest percentage of correct turns associated with the auditory display); at the low driving load, significant effects did not arise between the modality manipulation, however, at high driving load, the auditory display supported significantly better performance than the visual display.

Other studies either found no interaction of driving task load x modality in affecting IVT performance, or did not report results in a manner that would allow the form of the workload x modality interaction with secondary task performance decrements to be inferred.

Secondary Task Workload

Eight studies examined how varying IVT workload affected differences between auditory and visual delivery of IVT information on driving and IVT performance (Dingus et al., 1994; Liu, 2001; Walker et al., 1990; Ranney et al., 2002; Srinivasan & Jovanis, 1997; Labiale, 1990; Mollenhauer et al., 1994; Horrey & Wickens, 2002). Of the eight studies that manipulated IVT workload, four studies found that an increase in IVT complexity led to an increased auditory benefit for some aspect of the driving task (Liu, 2001; Walker et al., 1990; Dingus et al., 1990; Labiale, 1990). In all four studies, an advantage of shifting from visual to auditory delivery of IVT information on some aspect of performance of the primary driving task was amplified as the complexity of the side task increased. Stated in other terms, as the side task complexity increased, there was an increasing advantage of freeing up visual capacity from the side task, as reflected in performance of the primary driving task. The remaining four studies in this group did not reveal that the auditory-visual differences in task driving task performance were modulated by differences in IVT task complexity.

The effects of increased IVT workload on IVT performance were mixed. Liu (2001) found an auditory benefit to the IVT load increase, showing that under the complex secondary task condition, a greater decrement in response time and error rate was evident for the visual modality compared to the auditory modality and multimodality; the IVT performance was equivalent for the visual and auditory modalities under low IVT workload conditions. In contrast, Labiale (1990) found that under high workload conditions, visual presentation of IVT information results in better recall performance than auditory presentation of IVT performance; IVT performance is equivalent at low workload conditions. However, the findings from Labiale's study regarding the primary task, as reported in the previous paragraph, suggested that at higher workload levels, drivers better protect the higher-priority driving task when they use the auditory displays. Therefore, their sacrifice of the auditory displayed IVT performance at high workload can be seen to be "optimal." Walker et al. obtained consistent results with those of Labiale. As IVT workload increased, this increase had a negative impact on the accuracy of IVT performance with the auditory display, but not with the visual display. Three studies did not find an interaction of modality with secondary task load in their effects on driving performance and IVT performance (Horrey & Wickens, 2002; Ranney et al., 2002; Mollenhauer et al., 1994).

Workload Conclusions

In conclusion, the results of studies in which workload has been manipulated reveal a somewhat consistent picture. Increasing driving load will be more likely to increase (or produce) than to decrease the benefits of auditory IVT delivery to driving performance, particularly when the IVT is driving-related. The increased workload may, less consistently, increase the auditory benefits to performance of the IVT task itself. Increased IVT complexity (i.e., longer messages on the IVT) will also generally increase the benefits to driving of the auditory delivery of that information, but in particularly, such an increase may **not** increase the dual task benefits of auditory delivery of the IVT information to performance on the IVT task itself. This null effect may result from the inherent difficulty of processing long (i.e., complex) sequences of auditory information. However the well-calibrated driver apparently does not allow this increase in difficulty, associated with more complex auditory messages, to disrupt performance on the driving task itself.

2.5 Redundancy Gain

The 1994 study by Dingus, Hulse, McGehee, and Manakkal compared route guidance displays that employed redundant auditory and visual information versus visual information alone. The study revealed that cognitively demanding secondary tasks did not affect driving performance when information was presented with redundant displays but did affect driving performance when increased visual attention was required with the use of visual only displays. This result supports the idea that drivers are skilled at integrating complex (relevant) driving information when they are able to offload the information to the auditory modality. Four additional studies in our review compared redundant AV presentation, with the single mode (A, V) conditions (Liu, 2001; Dingus et al., 1997; Parkes & Burnett, 1993; Srinivasan et al., 1994). Of these, Liu (2001) reports that redundant auditory-visual display is as good as, but not better than auditory display (which was better than the visual display), when the message was of high complexity. Dingus (1997) and Parkes & Burnett (1993) report that redundant auditory-visual display has an equivalent influence on primary driving performance to the auditory and visual displays, but is generally better than the best of the auditory display and visual display for processing the information conveyed by the in-vehicle task. The Srinivasan et al. study (1994) relates that redundant auditory-visual display performs better than the visual display for both driving performance (RT to unexpected external events) and secondary-task performance measures.

It is important to note here that in some other studies, redundant presentation has not always lead to better performance than the best, or even the poorer of the two single modality display conditions (Helleberg & Wickens, 2002). The explanation of this “redundancy cost” lies in the participant’s inability to use the redundant information in the manner intended; namely to enable the auditory channel to convey information while vision is directed on critical primary task information, but only later, to allocate visual attention to the secondary task (when time allows) if that information that had been conveyed to the ears is forgotten.

2.6 Conclusion

The research reviewed above indicates at least five important variables that may moderate the relative degree of success in moderating a visual→ auditory delivery for an IVT: (1) the extent to which the IVT is relevant or irrelevant to the driving task; (2) the location (head up versus head down) of visual display that delivers the IVT information, (3) the workload of the ongoing driving task; (4) the complexity of the IVT information; (5) the extent to which information is presented redundantly along both channels.

ADDITIONAL REFERENCES (NOT INCLUDED IN THE APPENDIX)

Helleberg, J. & Wickens, C.D. (2002, in press). The effects of data link modality and display redundancy on pilot performance: an attentional perspective. *International Journal of Aviation Psychology*.

Latorella, K.A. (1998). Effects of modality on interrupted flight deck performance: implications for data link. *Proceedings of the 42nd Meeting of the Human Factors and Ergonomics Society (*pp 87-91). Santa Monica, CA: Human Factors Society.

Tindall-Ford, S., Chandler, P., & Sweller, J. (1997). When two sensory modes are better than one. *Journal of Experimental Psychology: Applied*, 3(4), 257-287.

Wickens, C.D., & Hollands, J. G. (2000). *Engineering psychology and human performance*. Upper Saddle River, NJ: Prentice Hall.

APPENDIX

The following table details the components of the 4 categories of the literature review template:

Study citation
IVT Task: **Describes the IVT task** *Visual information*: **Explains how the IVT information is presented in visual form** *Auditory information*: **Explains how the IVT information is presented in auditory form** *Separation*: **Gives the distance of the IVT from the driver's line of sight** *Manipulation of IVT Workload*: **Details how the IVT workload was manipulated**
Primary vehicle control task: **Describes the primary driving task (in a simulator or real driving)** *Manipulation of primary task load*: **Details how the primary driving task workload was manipulated**
Effect of modality manipulation on primary task: **Categorizes whether the auditory or visual display was better with respect to the primary driving task performance** *Main effect F value/p-value*: **Reports statistics on main effects** *Effect size*: **Reports statistics on effect size** *Interaction with WL*: **Reports statistics on the primary task interaction with the primary task workload manipulation** *Third task effect with modality manipulation*: **Reports statistics on any third tasks present in the study (hazard events included)**
Effect of manipulation on IVT task: **Categorizes whether the auditory or visual display was better with respect to the secondary IVT task performance** *Main effect F value/p-value*: **Reports statistics on main effects** *Effect size*: **Reports statistics on effect size** *Interaction with WL*: **Reports statistics on the secondary task interaction with the IVT workload manipulation**

AV Tabular Form (Driving Studies Only)

I. Primary Task: A > V; Secondary task: A > V

1) Burnett, G.E., and Joyner, S.M. (1997) An assessment of moving map and symbol-based route guidance systems. Noy, Y. Ian (Ed). Ergonomics and safety of intelligent driver interfaces. Human factors in transportation. (pp. 115-137). Hillsdale, NJ, US: Lawrence Erlbaum Associates, Inc. xvi, 432pp.
IVT task: Navigation task (Driving to a destination with a list of instructions) *Visual information*: Electronic (moving) map-based route guidance system with distance, direction, and route information *Auditory information*: Standardized verbal instructions (route/directional information) given from experimenter sitting in the passenger seat. *Separation*: A separate unit (5.75" monochrome CRT) near the center of the cockpit (approx. 5^o below line of sight). *Manipulation of IVT Workload*: n/a
Primary vehicle control task: Real driving *Manipulation of primary task load*: n/a
Effect of modality manipulation on primary task: Auditory > Visual; With respect to driving performance (measured by vehicle speed, steering wheel position, and indicator use). *Main effect F value/p-value*: steering wheel variability significantly greater for visual versus auditory display ($p < .05$) *Effect size*: n/a *Interaction with WL*: n/a *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Auditory > Visual; With respect to navigational performance (measured by navigational errors). *Main effect of F value/p-value*: navigational errors significantly greater for visual versus auditory displays ($p < .05$). *Effect size*: n/a *Interaction with WL*: n/a

2) Dingus, T.A., Hulse, M.C, McGehee, D.V., & Manakkal, R. (1994). Driver Performance Results from the Travtek IVHS Camera Car Evaluation Study. Proceedings of the Human Factors & Ergonomics Society 38th Annual Meeting, p. 1118-1122.
IVT Task: Navigation task *Visual information*: full, heading-up route map; graphic representation of static turn-by-turn information; textual paper direction list with large legible font; conventional paper map *Auditory-Visual information*: visual information WITH redundant aural messages *Separation*: not given *Manipulation of IVT Workload*: turn-by-turn displays versus route maps
Primary vehicle control task: real driving (1992 Oldsmobile Trofeo) *Manipulation of primary task load*: n/a
Effect of modality manipulation on primary task: Auditory > Visual (as measured by mean velocity, number of lane deviations) *Main effect F value/p-value*: not given *Effect size*: not given *Interaction with WL*: turn-by-turn significantly fewer number of lane deviations than route map *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Auditory > Visual (as measured by subjective workload, number and mean duration of glances, trip planning time) *Main effect F value/p-value*: subjective workload: turn-by-turn with and without voice had significantly lower reported workload than route map without voice; number of glances: turn-by-turn and route map with voice had significantly fewer number of glances than turn-by-turn and route map without voice; trip

planning time: $F(5,136) = 83.59$, $p < .0001$) – turn-by-turn with and without voice and route map with voice exhibited shortest trip planning times over route map without voice and paper map
Effect size: not given
Interaction with WL: n/a

3) Gish, K.W., Staplin, L., Stewart, J., & Perel, M. (1999). Sensory and Cognitive Factors Affecting Automotive Head-Up Display Effectiveness. Proceedings of the 78th Annual Transportation Research Board. Washington, D.C.: Traffic Safety Division, 1999.

IVT task: Navigation task (Navigating a route using a list of instructions; Prior to a turn opportunity, navigation instructions were presented on an in-vehicle display (HDD). The name of the upcoming street was presented simultaneously and participants were instructed to determine if the street name was present in the navigation instructions; a button press was used to indicate their response. This was designed to be a cognitive task.)
Visual information: list of text instructions
Auditory information: list of auditory text instructions (1 line at a time)
Separation: 20 degrees below the line of sight
Manipulation of IVT Workload: n/a
Secondary IVT tasks: Speed monitoring task (participants indicated through button press if two number presented either visually or aurally were the same – a response and somewhat cognitive task).
Collision Avoidance task (participants indicated through a braking response when they were presented with a warning either visually or aurally – a response task)

Primary vehicle control task: fixed-based, part-task driving simulator with 30 degrees horizontal field-of-view
Manipulation of primary task load: (daytime vs. nighttime ambient lighting conditions)

Effect of modality manipulation on primary task: Auditory > Visual;
Driving performance (as measured by % correct brake responses to unexpected events, which occurred 6 times per condition) was significantly better for auditory versus visual display, $F(2,66) = 16.64$, $p < .0001$.
Driving performance (as measured by brake response time to unexpected external events was significantly better auditory versus visual displays, $F(2,66) = 16.66$, $p < .0001$. Auditory presentation interfered the least with external target detection.
Main effect F-value/p-value: $F(2,66) = 16.64$, $p < .0001$; $F(2,66) = 16.66$, $p < .0001$
Effect size: approx. 10% more correct braking responses to external stimuli with Auditory versus Head-Down displays; approx 300 ms faster brake response time to external stimuli with Auditory versus Head-Down displays.
Interaction with WL: n/a
Third task effect with modality manipulation: n/a

Effect of manipulation on IVT task: Auditory > Visual;
Secondary task performance (as measured by % correct in-vehicle responses to navigation task) was better for auditory than visual stimuli. However, this may be due to the simplified auditory navigation task where just one navigation instruction was presented to the participant at a time for comparison to the simultaneous upcoming street name. Secondary task performance (as measured by % correct in-vehicle response to speed monitoring task) was better for auditory versus visual.
Main effect F value/p-value: n/a
Effect size: approx. 10% more correct in-vehicle responses to both the navigation task and the speed monitoring task with the Auditory versus Head-Down displays
Interaction with WL: n/a

4) Liu, Y-C. (2001). Comparative study of the effects of auditory, visual, and multimodality displays on drivers' performance in advanced traveler information systems. Ergonomics, 44 (4), 425-442.
IVT task: Navigation information task. Participants were instructed to follow the navigational instructions (auditory or visual) in the navigation task. *Visual information*: route guidance map; icons of vehicle status and roadway, text messages. *Auditory information*: aural text message containing roadway-relevant information or route guidance information. *Visual-Auditory information*: visual and auditory information combined (Both modalities utilized the following generalized information units: geographical entities, type of road, position, or instruction). *Separation*: LCD display (11.4x8.4 cm) mounted centrally above the dashboard (approx. 24^{o} to the left of the top of the steering wheel) *Manipulation of IVT Workload*: Participants performed the navigation task and button-pushing task under both high (visual: between 9 and 14 information units, aural: message every 5-8 s) and low (visual: between 3 and 5 information units, aural: message every 20+ s) workloads. *Additional secondary task*: Push button task - In the push button task, participants were informed either visually or aurally of vehicle condition information. They were instructed to manually respond to the vehicle information by either categorizing it as road condition info or vehicle condition info.
Primary vehicle control task: simulator (dome environment – 50x40 degree field of view) *Manipulation of primary task load*: Two levels of load (high and low) driving conditions as defined by lane width, road type, number of easy curves, number of sharp curves, speed limit, traffic density, and number of intersections
Effect of modality manipulation on primary task: Auditory > Visual with respect to driving performance (measured by variance in lateral acceleration and lane position, and variance in steering wheel position). *Main effect F value/p-value*: High driving load: lateral acceleration variance (F(2,60) = 3.86, p = .0266); lateral lane position variance (F(2,60) = 5.76, p = .0051); steering wheel position variance (F(2,60) = 4.18, p = .0199). Low driving load: mean absolute velocity deviation (F(2,60) = 10.69, p = .0001) (greatest deviation for visual); number of major lane deviations (F(2,60) = 3.92, p = .0251) (greatest for AV over V or A) *Effect size*: High driving load: lateral acceleration variance (.013 m/s^2 more for visual than auditory); lateral lane position variance (.6182 m more for visual than auditory), steering wheel position variance (.0152 radians more for visual than auditory). Low driving load: mean absolute velocity deviation (.66 m/s more for visual than auditory); number of major lane deviations (auditory 16, visual, 17, multimodality 31). *Interaction with WL*: High Driving Load: variance of lateral acceleration (F (2,60) = 3.19, p = .048); variance of lateral lane deviation (F(2,60) = 6.75, p = .00023); variance of steering wheel position (F(2,60) = 9.63, p = .0002; frequency of major lane deviations (F(2,60) = 22.09, p = .0001; (greatest for all when using visual display under complex information condition) Low Driving Load: variance in steering wheel position (F(2,57) = 3.56, p = .0351); variance for mean absolute velocity deviations (F(2,57) = 9.36, p = .0003); ; (greatest for all when using visual display under complex information condition) *Third task effect with modality manipulation*: RT: interaction between display modality and information complexity (F(2,60) = 14.61, p = .0001); Slower RT for visual modality under complex information condition [(F(1,186) = 22.29, p=.0001 for auditory versus visual – 3.247s vs. 5.081s), (F(1,186) = 1.48, p = .2259 for auditory versus multimodality – 3.247s vs. 2.792s), (F(1,186) = 35.02, p =.0001 for visual versus multimodality – 5.081s vs. 2.792s)]. Missed button pushes: multimodality display produced fewer misses (29) than those of the auditory condition (75) or the visual condition (110) [F(2,60) = 31.32, p = .0001].
Effect of manipulation on IVT task: Auditory > Visual with respect to information processing (measured by RT to button-pushing task and accuracy, total correct turns, vehicle control, and navigation-related errors to navigation task). Results consistent across workload. *Main effect F value/p-value*: Percentage of correct turns (high driving load only): visual display showed the lowest percentage of correct turns (F(1,186) = 5.12, p = .0248 for auditory versus visual and F(1,186) = 9.68, p = .0022 for visual versus multimodality). *Effect size*: percentage of correct turns (high driving load only): visual (90.63%), auditory (96.88%), multimodality (99.22%). Navigation-related errors: Misses (simple information): 7 visual to 4 auditory;

Wrong turns (complex information): 0 visual to 14 auditory. *Interaction with WL (information complexity)*: not given (however, in general – the greater the complexity of information, the greater the difference in performance between visual and auditory displays)

5) Srinivasan, R., Yang, C., Jovanis, P., Kitamura, R., & Anwar, M. (1994). "Simulation Study of Driving Performance with Selected Route Guidance Systems." In *Transportation Research, vol. 2C*, no. 2, 1994, pp. 73-90.
IVT task: In-vehicle route guidance system. *Visual information*: electronic map with display of streets (half-mile scale), text of intended route, text on the distance to destination and distance to turn, and driver's position icon; *Auditory-Visual information*: In conjunction with an electronic map, aural text message including information on distance to next turn, type of road, name of road. *Separation*: navigation device located in the dashboard (approx. 23^o below line of sight) *Manipulation of IVT Workload*: n/a
Primary vehicle control task: fixed-base simulator (170 degrees field of view) *Manipulation of primary task load*: 3 types of roadway (parkway type, urban four-lane undivided arterials, urban two-lane undivided arterials, each driving trial consisted of segments from the 3 types of roadway)
Effect of modality manipulation on primary task: Auditory-Visual > Visual; With respect to driving performance (measured by RT to unexpected external events (e.g. pedestrians, crossing vehicles, turning vehicles, traffic signal events, obstacles)). *Main effect F value/p-value*: Route guidance type (Chi square = 10.068, p = .018); Electronic (visual) map is associated with significantly smaller reaction times compared to the other systems (p = .005). *Effect size*: n/a *Interaction with WL*: n/a *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Auditory-Visual > Visual; With respect to navigational performance (measured by # and type of navigational errors). *Main effect F value/p-value*: n/a *Effect size*: n/a *Interaction with WL*: n/a

6) Streeter, L.A., Vitello, D., and Wonsiexicz, S.A. (1985). How to tell people where to go: Comparing navigational aids. International Journal of Man-Machine Studies, 22 (5), 549-562.
IVT task: Electronic map. *Visual information*: Customized route map – four-color schematic maps showing the route to be traveled in red (map included interturn mileages, landmarks, and the desired route). *Auditory information*: Verbal tape-recorded route messages (subjects operated the tape recorder and could repeat and play messages as desired). *Separation*: n/a (drawn maps) *Manipulation of IVT Workload*: n/a
Primary vehicle control task: real driving – conducted in a functional car on New Jersey roads *Manipulation of primary task load*: road type/categories (limited access, moderately difficult local routes, complicated local road routes)
Effect of modality manipulation on primary task: Auditory > Visual; With respect to driving performance (as measured by total driving time and total miles traveled). *Main effect F value/p-value*: driving time ($t_{30} = 2.47, p < .02$); optimal mileage ($t_{30} = 1.88, p < .07$) *Effect size*: driving time: auditory display yielded an average of 24 minutes per route whereas the visual display yielded an average of 26 minutes per route; optimal mileage: auditory display yielded more perfect mileage than visual display – optimal = 10.5 miles, auditory = 11.41 miles (7% more than optimal), visual = 12.72 miles (20% more than optimal). *Interaction with WL:* n/a *Third task effect with modality manipulation*: n/a

Effect of manipulation on IVT task: Auditory > Visual; Navigational errors decrease with auditory presentation of secondary task. *Main effect F value/p-value*: navigational errors ($t_{30} = 2.86$, $p < .01$) *Effect size*: 67% more errors made by the visual (map) than by the auditory (tape) group *Interaction with WL*: n/a

7) Walker, J., Alicandri, E., Sedney, C., and Roberts, K. (1990). In-vehicle navigation devices: Effects on the safety of driver performance. Performer: Federal Highway Administration, McLean, VA. Office of Safety and Traffic Operations Research and Development, p.107.
IVT task: Navigational task *Visual information*: visual device with route electronic and textual route information. *Auditory information*: audio device with aural text messages on direction and route specifications. *Separation*: a 4.9 x 5.5-inch CRT display located to the right of the driver approx. 20 degrees below the line of sight *Manipulation of IVT Workload*: complexity of visual display (high complexity: map of the area in the immediate vicinity of the driver, icon of driver's vehicle, directional arrows, destination icon, and destination distance; medium complexity: directions displayed with words and arrows; low complexity: direction of route displayed with arrow only); complexity of auditory display (high complexity: spatial directions (to parallel map); medium complexity: same text messages as in visual medium complexity displays; low complexity: directional indication of either "left" or "right").
Primary vehicle control task: FHA Highway Driving Simulator *Manipulation of primary task load*: Workload manipulated with the addition of crosswinds, another vehicle, gauge-monitoring, mental arithmetic problems, or narrowing lanes. Workload affected performance with respect to user preferences alone (lower complexity preferred over higher complexity).
Effect of modality manipulation on primary task: Auditory > Visual; With respect to driving performance (measured by speed control, and lateral deviation). *Main effect F value/p-value*: not given – auditory condition resulted in less lateral deviation *Effect size*: not given *Interaction with WL*: not given *Third task effect with modality manipulation*: (Perceptual loading task: monitoring the oil gauge (left side of steering wheel) and the temperature gauge (right side of steering wheel) in the dashboard. If either changed, the subject was to re-set the gauge by pressing a button above the respective gauges); (Cognitive loading task: a tape-recorded series of mental arithmetic problems with calculations involving a combination of distance to the next gas station and remaining fuel) In the Perceptual loading task: differences were largest for the complex visual and map devices ($F(6, 84) = 4.98$, $p = .0002$.
Effect of manipulation on IVT task: Auditory > Visual; With respect to number of navigational errors. *Main effect F value/p-value*: Average speed: navigational device ($F(6, 84) = 9.58$, $p = .0001$) – less speed decrement in auditory condition; Navigational errors: not given – but subjects made more errors with the visual display than with the auditory display *Effect size*: Visual errors: 31; Auditory errors: 9 *Interaction with WL*: Average speed: Navigational device x loading ($F(12, 168) = 3.28$, $p = .0003$) – the complex visual group had the lowest speeds; Navigational errors: X^2 (6) = 34.73, $p = .0001$), As complexity of task increased, visual errors decreased and auditory errors increased (Simple: V = 16, A = 0; Medium: V = 3, A = 1; Complex: V = 12, A = 8)

II. *Primary Task: A > V; Secondary Task: V > A*

1) Labiale, G. (1990). In-car road information: Comparisons of Auditory and Visual Presentations. In Proceedings of the Human Factors Society 34^{th} Annual Meeting (pp. 623-627). Santa Monica, CA: Human Factors Society.
EXPERIMENT 1: *IVT task*: Road information message display; In-car map information was presented either visually IVT map display or aurally; presentation of navigation information expected due to a pre-information warning tone. Visual information was displayed for a limited amount of time, calculated to allow only one read-through in order to compare to auditory constraints. Participants were instructed to memorize each road information message. Each map was displayed for 30 seconds. *Visual information*: Written text messages – categories of information included geography, type of road, position or direction, event-cause and event-consequence, time and distance, and action proposed. *Auditory information*: aural text messages of same categories as visual. *Separation*: A 9-inch, 23 cm diagonal fitted the right hand side of the instrument panel and oriented towards the driver. *Manipulation of IVT Workload*: 4 different lengths of message (4 information units, 7-9 units, 10-12 units, 14-18 units) *EXPERIMENT 2*: *IVT task*: In-car map display; In-car map information was presented either visually IVT map display or aurally. Participants were instructed to memorize the route to the destination for each map displayed. *Visual information*: route map + visual guidance (2-4 line messages) *Auditory information*: route map + auditory guidance (2-4 aural line messages) *Separation*: same *Manipulation of IVT Workload*: number of changes in the route direction (either 1 turn or 3 turns before reaching destination)
EXPERIMENT 1: *Primary vehicle control task*: real driving (2 km route) *Manipulation of primary task load*: n/a *EXPERIMENT 2:* *Primary vehicle control task*: same *Manipulation of primary task load*: n/a
EXPERIMENT 1: *Effect of modality manipulation on primary task*: Auditory > Visual; If low workload (less than 9 information units): Auditory = Visual. If high workload (greater than 9 information units): Auditory > Visual (as measured by vehicle speed and control). *Main effect F value/p-value*: at high workload: X2 = 8.5, p = .0003 *Effect size*: at high workload: 33.3% more affect on course control for visual versus auditory displays *Interaction with WL*: No stats (as WL increases, degradation of vehicle control and speed is greater for visual versus auditory displays) *Third task effect with modality manipulation*: n/a *EXPERIMENT 2:* Not available
EXPERIMENT 1: *Effect of manipulation on IVT task*: Visual = Auditory at low levels of workload (fewer- (< 14) pieces of information). Visual > Auditory at high levels of workload (14-18 pieces of information) (as measured by recall performance). Auditory > Visual for all levels of workload as measured by the number and duration of visual explorations. *Main effect F value/p-value*: overall: X2 = 1.1, p = .5; high levels of WL: X2 = 13.6, p < .0002 *Effect size*: 11.6% more correct replies during recall of memorized data for visual than for auditory displays. *Interaction with WL*: Increase in message length yields an increase in the average duration of each visual fixation (F(3,39) = 2.34, p = .086, a significant increase in the number of visual fixations (F(3,39) = 53.1, p

< .0001), and a significant increase in the overall duration of visual explorations (F(3,39) = 79.9, p < .0001). Additionally, as WL increases, recall performance decreases more for auditory versus visual displays.

EXPERIMENT 2:

Effect of manipulation on IVT task: Visual-Visual > Visual-Auditory (as measured by recall performance). Auditory > Visual for all levels of workload as measured by the number and duration of visual explorations.

Main effect F value/p-value: X2 = 2, p = .15

Effect size: 15.6% more correct replies during recall of memorized data for visual-visual than for visual-auditory displays.

Interaction with WL: Visual-Visual = Visual-Auditory at LOW Workload (1 turn); Visual-Visual > Visual-Auditory at HIGH Workload (3 turns), X2 = 7.8, p = .0005.

III. *Primary Task: A > V; Secondary Task: A = V*

1) Hurwitz, J., & Wheatley, D.J. (2002). "Using driver performance measures to estimate workload." . In Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting. p. 1804-1808.
IVT Task: Letter-monitoring task (a Computerized Continuous Performance Task – CPT). The letters "P," "T," "D," "B" are presented in random order. The subject is to press a button when the letter "P" appears *Visual information*: the letters were presented in a dialogue box on a computer screen at a rate of one every two seconds (with two seconds to make a response before an auditory beep sounded). *Auditory information*: the letters were presented over a speaker in the simulator at a rate of one per second (with one second to make a response before an auditory beep sounded). *Separation*: near the top of the dashboard and to the right of the steering wheel. *Manipulation of IVT Workload*: n/a
Primary vehicle control task: Driving simulator (KQ) *Manipulation of primary task load*: road type (a predominantly straight road, a predominately curvy road)
Effect of modality manipulation on primary task: Auditory > Visual (as measured by RMS change in steering wheel angle and RMS change in lane position) *Main effect F value/p-value*: (RMS steering wheel angle: Modality ($F(1,9) = 26.38$, MSE = .03, $R^2 = .75$)); *Effect size*: (RMS steering wheel angle: Visual – 1.252, Auditory – 1.054); (RMS lane position: Visual - *Interaction with WL*: (RMS steering wheel angle: Modality x Secondary-Task: ($F(1,9) = 5.98$, MSE = .031, $p < .05$, $R^2 = .4$) – The increase in RMS when the secondary task was presented was greater when the task was in the visual domain (.21) than when it was in the auditory domain (.03)); (RMS steering wheel angle: Modality x Track Interaction: ($F(1,9) = 8.57$, MSE = .039, $p < .02$, $R^2 = .49$) – the increase in RMS on the curvy track versus the straight track was larger on trips in which the visual secondary task was presented (RMS = 1.6) than on trips with the auditory task (RMS = 1.3)); (RMS lane position: Modality x Secondary Task Interaction: ($F(1,9) = 4.37$, MSE = 0, $p < .07$, $R^2 = .33$) – RMS was significantly higher when subjects performed the visual secondary task than when they performed the auditory secondary task, but only on the curvy track ($t(9) = 4.92$, SEM = .007, $R^2 = .73$)) *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: not reported (Auditory = Visual assumed) *Main effect F value/p-value*: n/a *Effect size*: n/a *Interaction with WL*: n/a

2) Ranney, T.A, Harbluk, J.L., & Noy, Y.I. (2002). The effects of voice technology on test driving performance: Implications for driver distraction. Proceedings of the Human Factors and Ergonomics 46th Annual Meeting (pp. 1814-1818). Santa Monica, CA: Human Factors and Ergonomics Society.
IVT Task: Search task (identifying a specified message and recording a voice memo containing the identified information) *Visual information*: text message *Auditory information*: a vocalized call initiated to an automated phone system *Separation*: n/a *Manipulation of IVT Workload*: complexity of task (more steps in search task)
Primary vehicle control task: Real driving (following task) – 1996 Honda Accord *Manipulation of primary task load*: n/a
Effect of modality manipulation on primary task: Auditory > Visual *Main effect F value/p-value*: Following distance: $F(3,57) = 8.65$, $p = .0017$ – for simple and complex tasks, drivers choose longer following distances when using the visual/manual interface; Steering Holds: $F(1,19) = 4.31$, $p = .052$ = the manual interface condition was associated with more holds than the voice condition. *Effect size*: n/a *Interaction with WL*: n/a *Third task effect with modality manipulation*: PDT accuracy: $F(1,19) = 5.81$, $p < .03$ – subjects detected

more peripheral targets while performing secondary tasks using the voice interface than they did while using the visual/manual interface; PDT RT: $F(1,19) = 7.05$, $p < .02$ – drivers responded more quickly to PDT targets while performing secondary tasks using voice interface than in the visual/manual interface condition.

Effect of manipulation on IVT task: Auditory = Visual
Main effect F value/p-value: not significant
Effect size: n/a
Interaction with WL: not significant

3) Srinivasan, R., Jovanis, P. (1997). "Effect of selected in-vehicle route guidance systems on driver reaction times." Human Factors. Vol 39(2) Jun 1997, 200-215.

IVT task: In-vehicle navigational system
Visual information: electronic map / turn-by-turn text message plus indication of direction;
Auditory information: aural text message including information on distance to next turn, type of road, name of road.
Separation: IVT located in the instrument panel to the right of the driver's forward field of view
Manipulation of IVT Workload: guidance information (electronic route map versus turn-by-turn display)

Primary vehicle control task: driving simulator (170^o field of view)
Manipulation of primary task load: 3 types of roadway (parkway type, urban four-lane undivided arterials, urban two-lane undivided arterials

Effect of modality manipulation on primary task: Auditory > Visual;
With respect to driving performance (measured by speed, reaction time to external events, and lane deviation).
Main effect F value/p-value: n/a
Effect size: n/a
Interaction with WL: RT to electronic map faster than to turn-by-turn display; auditory benefit increased with complexity of the driving situation.
Third task effect with modality manipulation: Scanning task (workload manipulation): Outlines of coral colored squares rotated on the left and right of the visual scene – subjects were asked to push a button when a square rotated 45 degrees – this rotation occurred within an interval of every 5-20 s.
Auditory > Visual;
With respect to roadside scanning task (measured by RT to scanning task); auditory vs. visual turn-by-turn significant at $p < .05$.

Effect of manipulation on IVT task: Auditory = Visual;
With respect to navigational errors (measured by correct route choice).
Main effect F value/p-value: n/a
Effect size: navigational errors: auditory (0), visual electronic map (0), visual turn-by-turn (2)
Interaction with WL: n/a

IV. *Primary Task: A = V; Secondary Task: A > V*

1) Parkes, A.M., and Burnett, G.E. (1993). An Evaluation of Medium Range “Advance Information” in Route-Guidance Displays for Use in Vehicles. IEEE Vehicle Navigation & Information Systems Conference, Ottawa, Canada.
IVT task: In-vehicle route guidance system; *Visual information*: navigational symbols (direction, own-ship), distance, and route text messages. (Visual symbols presented to drivers were of three types: advance information, straight ahead, or preparation. An auditory beep sounded before every text/symbol message appeared on screen). *Auditory-Visual information*: navigational information on direction, distance, and route through recorded speech messages and presented concurrently with visual information. *Separation*: 10-in. LCD screen mounted on vehicle dashboard centerline at height of steering wheel center *Manipulation of IVT Workload*: n/a
Primary vehicle control task: real driving *Manipulation of primary task load*: n/a
Effect of modality manipulation on primary task: Auditory-Visual = Visual; With respect to driving performance (measured by time to complete the route). *Main effect F value/p-value*: n/a *Effect size*: n/a *Interaction with WL*: n/a *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Auditory-Visual > Visual; With respect to navigational performance (measured by number and type of navigational errors, duration and frequency of display fixation). *Main effect F value/p-value:* duration of display fixation: $p < .05$; frequency of display fixation: $p < .05$ *Effect size*: duration of display fixation – 2.5% more time spent looking at display in visual only condition; frequency of display duration – 26% more frequent glances at display in visual only condition compared to visual-auditory condition. *Interaction with WL*: n/a

V. *Primary Task: A = V; Secondary Task: V > A*

1) Lee, J.D., Gore, B.F., Campbell, J.L. (1999). Display Alternatives for In-Vehicle Warning and Sign Information: Message Style, Location, and Modality. Transportation Human Factors, 1 (4), pp. 347-375.
IVT task: Advanced Traveler Information System (AVIS); drivers were asked to acknowledge each ATIS and roadway warning by pressing one of two steering-wheel buttons. *Visual Information*: text messages (conveying driving status for 6 different events: curve, crosswalk, icy roadway, road construction, accident in lane, HOV lane), *Auditory Information*: Verbal text messages identical in form to visual messages. *Separation*: display located in instrument panel directly in front of the driver *Manipulation of IVT Workload*: Message manipulation: Message style either command or notification.
Primary vehicle control task: Battelle automotive simulator *Manipulation to primary task load*: n/a
Effect of modality manipulation on primary task: Auditory = Visual; With respect to driving performance as measured by # crashes, lane position deviation, speed control, turn signal usage *Main effect F-value/p-value*: n/a *Effect size*: n/a *Interaction with WL*: n/a *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Visual > Auditory; With respect to message acknowledgement. *Main effect F-value/p-value*: response to message ($F(1,16) = 6.38, p < .05$) *Effect size*: response to message (response greater for visual messages, 92%, compared to auditory messages, 85.4% *Interaction with WL*: ATIS modality x message style: ($F(1,16) = 5.96, p < .05$) (drivers more likely to respond to visual command messages than auditory command messages). Summed across modalities, command messages compromised safety over notification messages (with RMS error, RMS lane position, and number of crashes greater for command).

VI. *Primary Task: A = V; Secondary Task: A = V*

1) Dingus, T.A., McGehee, D.V., Manakkal, N., Jahns, S.K., Carney, C., & Hankey, J.M. (1997). Human Factors Field Evaluation of Automotive Headway Maintenance/Collision Warning Devices. Human Factors, 39 (2), 216-229.
IVT Task: collision warning information display – monitoring headway distance *Visual information*: warning information displayed using a series of nine colored bars placed in perspective – as the distance between the participant's vehicle and the lead vehicle became shorter, new bars were displayed one below another, increasing in number and changing in color from green (1.6 sec or greater) to orange (1.1 – 1.6 sec) to red (.9 – 1.1 sec) tones. (At a distance of less than .9 sec., the red bars flashed on and off at a rate of 4 Hz). *Auditory information*: When entering the red zone (.9 - 1.1 sec), participants heard a voice message ("Look ahead"), the message was repeated every 7s if the headway did not increase out of the red zone. At less than .9s, the message changed ("Brake") and was repeated every 4 seconds if the headway did not increase out of the zone. *Auditory-Visual information*: a combined display of the visual information and the auditory information *Separation:* 5 x 7-inch diagonal LCD screen mounted in the dashboard next to an analog speedometer (approx. 23 degrees below line of sight) *Manipulation of IVT Workload:* n/a
Primary vehicle control task: Real driving (using a 1990 Oldsmobile Trofeo) *Manipulation of primary task load*: n/a
Effect of modality manipulation on primary task: Auditory = Visual *Main effect F value/p-value*: no significant differences *Effect size*: n/a *Interaction with WL*: n/a *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Auditory = Visual (as measured by mean headway in seconds) *Main effect F value/p-value*: no significant differences (when compared to their individual baseline measures: visual: $F(1,3) = 10.26$, $p < .05$; auditory: not significant; visual-auditory: $F(1,3) = 11.40$, $p < .05$ *Effect size*: n/a (when compared to their individual baseline measures: (visual: 1.47s to 2.05s), (auditory: 1.51s to 1.94s), (visual-auditory: 1.56s to 2.14s) *Interaction with WL*: n/a

VII. *Primary Task: V > A; Secondary Task: A > V*

**1) Lee, J.S. (1997). The effects of information modality and complexity of in-vehicle navigation system on drivers' information processing and vehicle control. Korean Journal of Experimental & Cognitive Psychology, 9 (2), pp. 43-61.
In-vehicle navigation system; Visual information: conventional road signs, Auditory information: female voice through a speaker conveying route information
Display manipulation: complexity of information (high vs. low frequency). RT in the auditory condition increased as amount of information increased.
Visual > Auditory; With respect to driving performance (measured by RT, accuracy, and driving distance).
Auditory > Visual; With respect to free recall performance or information processing (measured by RT and accuracy).

2) Mollenhauer, M.A, Lee, J., Cho, K., Hulse, M.C., & Dingus, T.A. (1994). The effects of sensory modality and information priority on in-vehicle signing and information systems. In Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting. p. 1072-1075.
IVT Task: road sign information – drivers expected to adhere to and recall sign information *Visual information*: relevant road sign information included current speed limit, current route number, the information presented on the last displayed sign *Auditory information*: auditory speech representations of road sign information *Separation*: LCD display located on top of the simulator instrument panel directly ahead of the driver (above the steering wheel but not interfering with the driving task) (approximately 11 degrees below the line of sight) *Manipulation of IVT Workload*: unfiltered (presentation of road sign information at the rate that a driver would see signs during a normal drive, at the posted speed limit) versus filtered (presentation of road information at HALF the rate that a driver would see during a normal drive).
Primary vehicle control task: fixed-base, interactive driving simulator (projected image of roadway environment encompasses 40 (vertical) x 50 (horizontal) degree field-of-view. *Manipulation of primary task load*: n/a
Effect of modality manipulation on primary task: Visual > Auditory (as measured by lane position deviations, steering wheel bandwidths, road-heading error, and speed variability) *Main effect F value/p-value*: lane position deviation – greater deviation for auditory: ($F(1,12) = 9.65$; $p = .009$); steering wheel rate – more rapid steering wheel movements with auditory ($F(1,12) = 14.20$; $p = .003$); road-heading error – more angular deviation between the actual road pathway and the heading of the vehicle with auditory: ($F(1,12) = 5.14$; $p = .04$); speed variability – average speed deviation greater with auditory: $F(1,12) = 5.55$; $p = .036$) *Effect size*: lane position deviation: approx. 2 cm more for auditory than visual *Interaction with WL*: n/a *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Auditory > Visual Auditory display type had a higher number of recalled sign information items *Main effect F value/p-value*: $F(1,12) = 18.09$; $p = .001$ *Effect size*: approx. 2 items across subjects *Interaction with WL*: not given (However, independent of modality, higher workload significantly decreased the number of recalled items).

VIII. *Primary Task: V > A; Secondary Task: V > A*

1) Matthews, G., Sparkes, T., & Bygrave, H. (1996). Attentional overload, stress, and simulated driving performance. Human Performance, 9(1), 77-101.
IVT task: Baddeley's (1968) Reasoning Test (utilizing grammatical transformation, i.e. subjects asked to judge whether simple sentences followed by a letter pair were true or false). Onset unpredictable. Priority or IVT and driving task varied: (driving prioritized vs. equal priority vs. reasoning prioritized). *Visual information*: items presented as overhead signs within the simulated driving scene *Auditory information*: items generated as computerized speech. *Separation*: overlaid *Manipulation of IVT Workload*: n/a
Primary vehicle control task: simulator *Manipulation of primary task load*: type of road section (straight or curvy)
Effect of modality manipulation on primary task: Visual > Auditory; Primary driving task (as measured by mean heading error or longitudinal error) was more disrupted by the auditory modality than the visual modality. *Main effect F value/p-value:* Distance (variability): $F(1,78) = 25.6$, $p < .01$ *Effect size*: Distance: .274 *Interaction with WL*: Interaction between modality and curvature: Heading error - $F(1,78)=9.0$, $p < .01$; dual-task interference found only in curve driving in the auditory condition *Third task effect with modality manipulation*: n/a
Effect of manipulation on IVT task: Visual > Auditory; The visual modality displayed no dual-task decrement (as measured by the accuracy of responses and RT to presentation of the stimuli). However, the auditory modality displayed decrement on the curved road sections relative to the straight-road sections. Accuracy of responses deteriorated as more priority was given to driving for both auditory and visual conditions. *Main effect F value/p-value*: n/a *Effect size*: n/a *Interaction with WL*: n/a

IX. *Primary Task: V > A; Secondary Task: A = V*

1) Horrey, W.J., & Wickens, C.D. (2002). Driving and Side Task Performance: The effects of display clutter, separation, and modality. Technical Report AHFD-02-13/GM-02-2, General Motor Corporation.
IVT Task: Digit callout task (read-back of digit strings) *Visual information*: digit strings presented in HUD/HDD display *Auditory information*: aural presentation of digit strings *Separation*: HUD (0^o below horizon line, 7^o below horizon line); HDD (center of console, approx. 38^o below horizon line) *Manipulation of IVT Workload*: digit length (4, 7, 10 digits)
Primary vehicle control task: KQ driving simulator *Manipulation of primary task load*: road type (urban, rural straight, rural curved)
Effect of modality manipulation on primary task: Visual > Auditory *Main effect F value/p-value*: Lane deviations: no significance; Speed control: $F(1,19) = 38.64$, $p < .001$ – auditory condition exhibited more variation in speed control relative to the HDD visual condition *Effect size*: approx. 0.1 s.d. *Interaction with WL*: not significant *Third task effect with modality manipulation*: not significant (hazard events) (Visual = Auditory)
Effect of manipulation on IVT task: Auditory = Visual *Main effect F value/p-value*: RT: $F(1,20) = 57.25$, $p < .001$ - shorter response times for the auditory condition compared to the HDD visual condition; Response Time: $F(1,20) = 3.96$, $p = .06$ - longer response times in the auditory condition relative to the HDD visual condition; Accuracy; $t(20) = -13.29$, $p < .001$ – costs for accuracy in the auditory condition compared to the HDD visual condition (particularly in highest-task load (10-digits)). *Effect size*: Reaction Time: Auditory (Mean = .39s), Visual (Mean = 1.08s); Response Time: Auditory (Mean = 3.17s), Visual (Mean = Mean = 2.88s); Accuracy: Auditory (Mean = .86), Visual (Mean = 1.0). *Interaction with WL*: not significant