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**In Vehicle Displays and Control Task
Interference: The Effects of Display
Location and Modality**

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Abstract

In-vehicle displays, whether in aircraft or in ground vehicles, can often divert visual attention away from critical information for vehicle path monitoring and control (i.e., tracking). This experiment compares two proposed solutions to this attention competition: (1) changing the location of the display, by moving it closer to the locus of tracking information, ultimately to a superimposed head up (HUD) position, and (2) changing the modality of presentation from visual to auditory. Twenty-four participants performed a 2 axis first order compensatory tracking task, while a simulated in-vehicle task of encoding and vocally responding to digit strings of various lengths was presented at unpredictable times. The digit side task could be presented at a HUD location, at any of 4 separations to the right of the tracking task, ranging from adjacent (7.5 degrees) to 45 degrees of visual angle, at any of two locations below the tracking task, or through the auditory modality.

The results revealed that: (1) auditory delivery of side task information "preempted" the tracking task, to the advantage of the side task, but at the cost of tracking performance; (2) spatial overlay (HUD) decreased the readability of the side task, with a small cost to tracking; (3) spatial separation at small visual angles had costs to both detecting the side task onset and tracking error. These costs were greater when displacement was downward than when it was leftward; and (4) greater eccentricity displacements delayed the initiation and completion of the side task response and, in particular, increased tracking error while the digit string responses were vocalized. Side task load varied by digit string length and generally had additive effects with display location.

Measures of tracking control activity were employed to diagnose the nature of the interfering effects. The results are interpreted in terms of their relevance to single channel theory, multiple resource theory, task switching theory, and theories of visual attention allocation.

Introduction

The vehicle control environment, whether in the air or on the ground, is visually intensive. Operators of both aircraft and ground vehicles are often provided with additional in-vehicle technology (IVT). This technology may be in the form of navigational aids or other communication devices in both of these operating environments. The addition of this new source of information may, however, create the possibility of visual overload (Wickens, Gordon, & Liu, 1998). Poor management of resource allocation by the pilot or driver between the various sources of information may therefore disrupt the monitoring and processing of safety-critical information for visual vehicle guidance, available out the window (or on a synthetic display). This diversion of visual attention could be catastrophic at critical times, such as the final approach to landing (air) or negotiating an intersection (ground).

While automation of several aspects of vehicle control is often proposed as a solution (e.g., autopilots and auto land capabilities for aircraft, cruise control, auto-steering and headway monitoring for cars), we do not consider this solution in the current paper, because our focus will be on situations where outside world (OW) command inputs and unexpected hazards must be monitored (for safety), no matter whether the operator is actively engaged in control, or passively observing automation accomplish that same control. For example, pilots flying an approach will closely monitor the OW for the runway threshold (i.e., when the runway becomes visible), and further use peripheral motion cues to help stabilize the aircraft. Drivers will monitor the road ahead for potential obstacles and hazards. To the extent that both operators fail to attend to these OW regions there may be serious costs to safety.

Two different human factors solutions have been proposed to mitigate the attention competition imposed by IVT: visual overlay and auditory presentation. We examine both of these in the current study.

Visual Overlay: The HUD and Spatial Separation

Visually overlaying the IVT information in a head up display (HUD) reduces three costs associated with conventional head down presentation: (1) the effort of rapidly scanning between IVT displays and the OW; (2) the probability of missing (or delaying response to) OW events while visual attention is focused on the IVT and (3) the degraded quality of peripheral information in the currently unattended region (i.e., reduced salience of OW information while focusing on an IVT display). It is important to note, however, that the overlay of IVT information on the OW may impose visual clutter costs, such that overlaid information can obscure the view of the OW, as well as being obscured itself by heterogeneous features of the OW (Wickens, Ververs, & Fadden, in press summarize the several studies in this area relevant to both ground and air vehicles.) A second cost of overlay, not addressed here, is the difficulty in providing appropriate levels of intensity or contrast of IVT imagery when it is presented on a HUD (Ververs & Wickens, 1998).

The effects of spatial separation between IVT and OW can be illustrated by a relatively complex function of information access costs which is both non-linear, and of different form for different sorts of tasks (Wickens, 1993; Schons & Wickens, 1993). These relations are depicted in Figure 1, which shows that at small angles of separation, the cost of scan is offset by the

benefits of reduced clutter relative to the overlay condition. Some evidence for the shape of the cost function is provided by research conducted by Schons and Wickens (1993) and Martin-Emerson and Wickens (1992), in which they varied the eccentricity of discrete processing tasks relative to a continuous tracking task, providing data that supported the general shape of the function shown in Figure 1. Small increases in separation impose only slightly augmented costs, because the near ballistic nature of eye movements allows longer saccades to be made in roughly the same time as shorter ones. However, outside the “eyefield” (at approximately 20° separation), head movements become increasingly necessary (Bahill, Alder, & Stark, 1975; Previc, 1998, 2000) and their costs increase with eccentricity, due to their non-ballistic characteristics. The nature of this function may, however, be influenced by the visual requirements of the task. For example, the tracking task, which is characteristic of most OW vehicle control environments, can be successfully accomplished with ambient vision, available (but degraded) in peripheral vision (Levison, Elkind, & Ward, 1971; Previc, 1998; Wickens, 1986; Martin-Emerson & Wickens, 1992). In contrast, many tasks involving both reading and object classification require focal vision, restricted primarily to a few degrees of visual angle around the fovea (Previc, 1998). Hence these tasks will require an eye movement to be accomplished. A theory of vision in 3D space proposed by Previc (1998) postulates that tracking or spatial guidance tasks will be better performed in the lower and left visual field than in the upper and right visual field, whereas tasks requiring high acuity or pattern recognition (e.g., print perception) will show the opposite form of asymmetry. These relationships have been partially supported by empirical research (Sochacki & Wickens, 1997; Wickens, Sandry, & Hightower, 1982; see Wickens, 1986 for a summary).

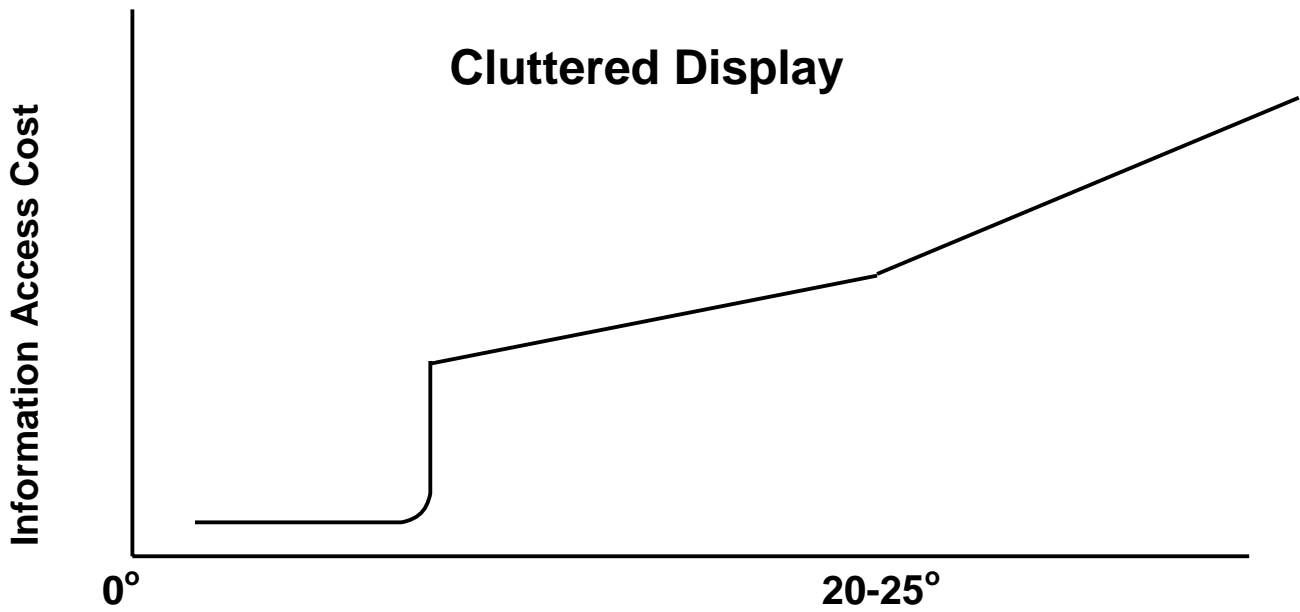
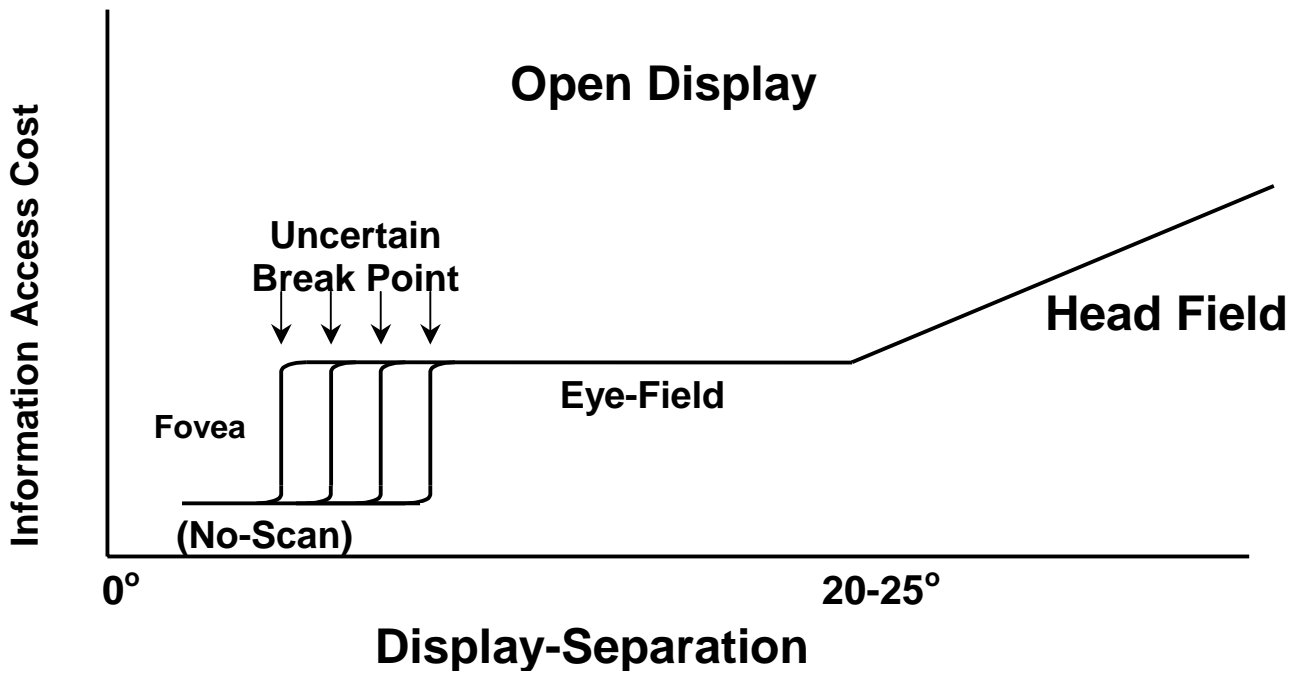


Figure 1. Information access as affected by spatial separation. From Wickens (1993).

Auditory Presentation

An alternative to overlay is to present IVT information auditorally. In the following, we refer to this solution as “aV” to designate an auditory (**a**) IVT coupled with a primary visual (**V**) OW vehicle monitoring and control task. (We use a lower case letter to represent the IVT side task modality because it should be considered a secondary task in the context of a primary (visual) vehicle control task.) The aV solution alleviates visual scanning, as does the HUD overlay but unlike the HUD, auditory delivery does not impose the offsetting cost of clutter. Intuitively, auditory presentation (aV) would seem to offer considerable benefits when the alternative is a visual IVT display (vV) that is widely separated from the OW. Such a visual display would require scanning and the use of peripheral vision to process both primary and secondary sources of information. Furthermore, even when the vV configuration does not involve extensive scanning, there is still evidence of an advantage of the aV presentation, based on the concept of multiple processing resources (Navon & Gopher, 1979; Meyer & Kieras, 1997; Schumacher, Seymour, Glass, Fencsik, Lauber, Kieras, & Meyer, 2001; Wickens, 1980, 1991, 2002). Multiple resource models posit that two visual tasks (i.e., the IVT task and the vehicle guidance task) must compete for a limited supply of visual processing resources, whereas in the aV configuration, each task benefits to some extent by unique access to non-sharable, modality-specific processing resources. The advantage of such cross modality processing, even when scanning is eliminated in the vV case, has been well documented in the literature (see Wickens, 1980, 1991 for a review).

It is also the case that the relative advantage of aV over vV may be moderated by five key factors, which will be a focus of the reported experiment.

First, as can be inferred from Figure 1, any relative advantage of aV over vV will grow to the extent that the vV condition involves greater spatial separation. Second, different task pairs may compete, in varying degrees, for common **perceptual** resources (as opposed to the distinct availability of unique sensory resources). For example simultaneous reading and listening to text will create considerable resource competition for perceptual language decoding despite the use of separate modality resources. To the extent that these common perceptual demands are high, then less advantage may be gained by distributing sensory processing across unique AV sensory resources. (A common fallacy is to assume that multiple resource theory, in particular the four-dimensional multiple resource model of Wickens (2002), predicts perfect time-sharing when separate modalities are employed. It does not make such predictions, since the perceptual processing upon which the A and V channels both depend, is itself resource-limited.)

Third, any comparison between aV and vV conditions in an IVT/Tracking dual task combination should account for the fact that the comparison of auditory and visual delivery of the IVT task information may be confounded by differences in the single task **compatibility** between input modality and cognitive processing code of the IVT (Vidulich & Wickens 1986). Such compatibility differences will influence single task resource demand, and these demand differences will in turn influence dual task resource competition, for reasons unrelated to multiple resources. In particular, a program of research has suggested that verbal tasks (e.g., retention of a short digit or word sequence) are inherently more compatible when supported by auditory (speech) input than by visual (text) input, whereas spatial tasks (e.g., map understanding) are inherently more compatible when supported by visual analog input, than by

auditory input (Wickens, Sandry, & Vidulich, 1983; Wickens, Vidulich, & Sandry-Garza, 1984; Vidulich & Wickens, 1986). Thus, when a comparison of aV with vV is made for a verbal IVT, any advantages to an aV configuration could be attributable as much to compatibility benefits of the auditory side task reducing its resource demand, as to benefits of separate resources.

The fourth mitigating factor, **preemption**, is one that is based on findings that auditory delivery of side task information is not always as benevolent to an ongoing visual (tracking) task, as separate (multiple) resource predictions would suggest. Indeed Wickens and Liu (1988) reviewed a wide range of aV versus vV experiments and found that many of them revealed benefits of auditory presentation, in terms of reduced performance decrements in dual task conditions relative to single task conditions—a finding consistent with multiple resource theory. However, they also note that the performance of the visual primary task (usually a tracking task) **suffered** a cost from the auditory display of side task information, as if the auditory side task presentation “preempted” tracking performance, in a way that the visual task did not. We hypothesized that this preemption effect might have been related to the intrinsic attention capturing features of the auditory modality (Spence & Driver, in press), a property that has led to its consistent use as a warning and alerting sense. We refer to this factor as “onset preemption.”

The fifth factor is a different form of preemption from the onset preemption described above, which is more strategic in nature. If the auditory modality delivers a long string of verbal information that needs to be rehearsed in working memory so that it is not forgotten, then the vehicle operator might choose to deal with the IVT information immediately, allocating most resources to the IVT upon its arrival (the resources allocated would be general perceptual-cognitive resources, not specific sensory resources). Visual delivery of IVT information, being more “permanent” (i.e. displayed) would not require such immediate use, and the operator could deal with that visual IVT information when time allows (e.g., intermittently, or at times when the OW control task is of low demand). Evidence of this strategic form of auditory preemption has been provided by studies of delivery of pilot communications over voice versus visual data-link channels (Latorella, 1998; Helleberg & Wickens, 2002).

In conclusion, given the complexity of factors modulating the aV – vV difference, it is difficult to make any absolute predictions regarding which modality interface is superior. However it is possible to offer predictions regarding how the relative differences in effectiveness between them will be modulated. For example, aV performance will be improved relative to vV performance to the extent that:

- vV separation is greater (a benefit for both the primary and IVT tasks) the two modalities define a separate resource (a benefit for both tasks)
- the onset of the IVT is abrupt, attention-capturing, and possibly unpredictable thereby creating the preemption effect (an auditory benefit only for the IVT)
- the message is verbal and complex, requiring rehearsal, thereby inducing strategic auditory preemption (an auditory benefit only for the IVT)

In contrast, the vV configuration is inferred to be better (or less inferior) to the extent that:

- the visual displays are adjacent, or possibly overlapping.
- the visual channel provides a more compatible means of presenting spatial IVT information.

A host of studies have compared auditory versus visual delivery of dual task information (see Wickens, 1980, 1991; Wickens & Liu, 1988 for a review), and a substantial proportion of these have used tracking or vehicle control as one of the tasks; furthermore, some studies have also examined spatial separation in a dual task environment. However, no study appears to have contrasted both overlay and modality solutions within the identical dual task paradigm, typical of the pilot or driver coping with vehicle control and an IVT, so that a comparison of the HUD and the auditory display solutions (“which is better under which conditions”) could be made by the system designer. The intention of the current study is to provide such data.

To examine these issues, participants carried out a 2-axis tracking task, representing the primary task of vehicle control, while performing a simulated IVT consisting of reading or hearing, and then vocally recalling digit strings. These digit strings were delivered at unpredictable times, over either visual or auditory channels. Visual channels were presented in blocked conditions across an array of visual separations, ranging from HUD (overlay) to a visual angle of 45 degrees. To test specific hypotheses regarding the use of peripheral vision for tracking, separation was also imposed both laterally and vertically. In the analysis, the visual separations were blocked into two categories in order to address the eye field and the head field separation ranges. The eye field region included separations of between 7 (VH1, VV1) and 15 degrees (VH2, VV2), while the head field region included separations of beyond 15 degrees (only in the horizontal direction). Finally, to discriminate between the influences of onset preemption and strategic preemption, the digit string was varied in length, in a way that imposed varying needs for rehearsal of the auditory string.

Our analysis focused primarily on the decrement from single task tracking error to its dual task level in the varying conditions and upon two aspects of the IVT performance: (1) the response time (RT), or latency to initiate the first digit of the response string following stimulus onset, and (2) the actual “speech time” (ST) required to speak the full string. Recall accuracy was also assessed.

A final measure, “tracking response velocity” was assessed as a means of inferring the degree of resource allocation to the tracking task (Wickens, 1986). We inferred that a condition of preemption that might induce a full switch of attention away from the tracking task, would not only increase tracking error, but would also lead to a total cessation of tracking behavior, bringing stick movement to zero. This behavior would be typical of single channel or bottleneck models of information processing (Welford, 1967; Pashler, 1998; Liao & Moray, 1993). In contrast, conditions of minor interference would only lower tracking stick movement, as this measure has been found to reflect the level of resource allocation to a tracking task (Wickens & Gopher, 1977; Wickens, 1986; Fracker & Wickens, 1989; Tsang, 1997). Finally, conditions that degrade the quality of visual information (i.e., peripheral viewing) might not reduce velocity at all, even as the lower quality input would be expected to elevate tracking error.

Thus, we use response time, speech time, tracking error and tracking response velocity as diagnostic indicators of the patterns of interference, induced by qualitatively different manipulations on the dual task combination display: modality, overlay, and spatial separation – in the eye field (both vertically and laterally), and in the head field.

Methods

Experimental Tasks

Participants were asked to perform two tasks: 1) a primary tracking task and 2) a secondary digit-recall task. The tasks were displayed on two Dell SVGA 19-inch computer monitors that were placed directly adjacent to each other. The tracking task was located in a 256 x 256 pixel area in the top left corner of the left-hand monitor. The secondary task appeared visually in any one of seven areas (see Figure 1) or auditorally. Subjects used a joystick trigger to indicate the beginning of their voice response, while the experimenter used the keyboard to indicate when participants had completed their response and also to assess correct or incorrect responses.

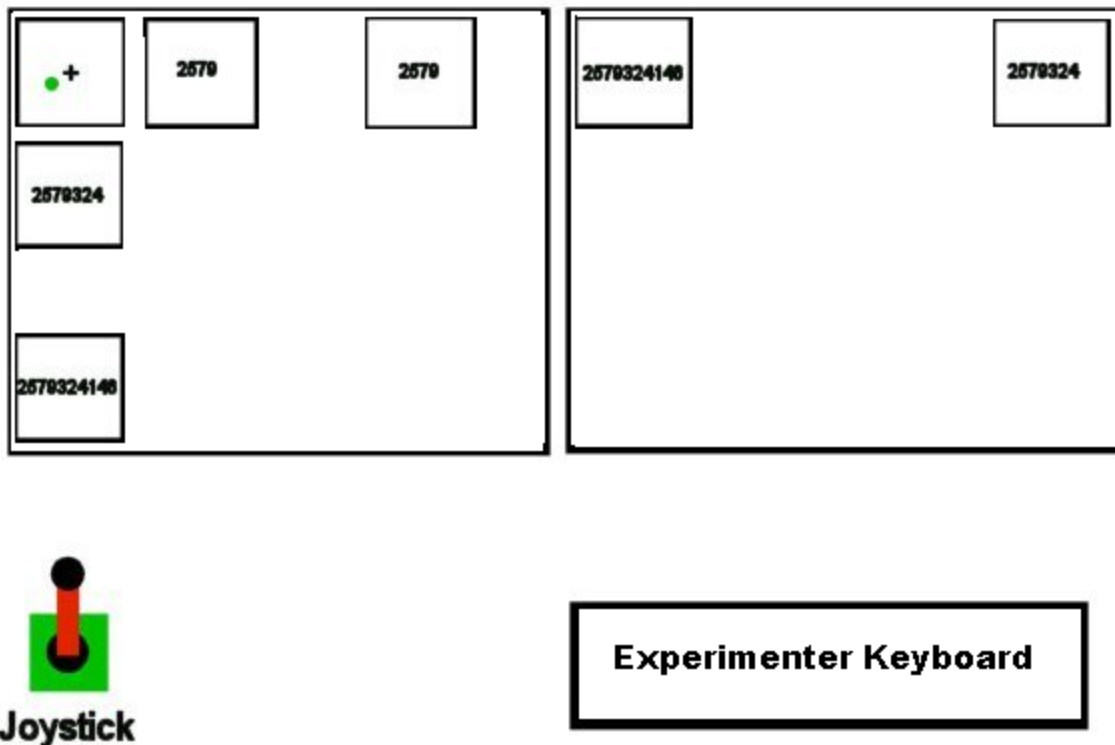


Figure 1. The experimental tasks. The symbols and numbers are proportionally larger than in the actual experiment. Examples of different digit load stimuli are shown.

Tracking Task

The compensatory 2 axis tracking task consisted of black '+' symbol in the middle of the tracking area, and a cursor that was driven in each axis by sum of 3 sine waves. Three of the sine waves summed together for the horizontal disturbance in amplitude (69.0 mm, 32.0 mm, 17.0 mm) and frequency (.08 Hz, .5 Hz, .3 Hz), and the three others for the vertical disturbance in amplitude (55.0 mm, 39.0 mm, 24.0 mm) and frequency (.05 Hz, .2 Hz, .08 Hz). At the maximum, the sine waves added up to +/- 118, or 10 pixels away from the box edge. This made the tracking input completely unpredictable. The participants' positional error was recorded continuously.

Secondary Task

The secondary task or side task involved two modalities: 7 visual configurations and 1 auditory configuration. Each of the 8 trials had three levels of difficulty or "side task load": 4-digit, 7-digit, and 10-digit numbers. Within each 180-second tracking configuration (234 seconds for the auditory configuration to take into account the time it took to listen to the auditory messages), 18 numbers—evenly distributed among the levels of difficulty—appeared on one viewing angle. The participants were informed before each block which viewing angle the numbers would be appearing in. The side task events were presented with an interstimulus interval of 10 (+/- 4) seconds.

The display boxes for each of the side tasks were 256 x 256 pixels in size (7.46 x 7.46 degrees). The size of the digit strings with respect to visual angle were as follows: 0.92 degrees for the 4-digit strings, 1.58 degrees for the 7-digit strings, and 2.33 degrees for the 10-digit strings; the height of the digit strings was 0.33 degrees visual angle. One of the visual configurations overlaid the tracking task (i.e., the digits appeared directly on top of and centered over the '+' symbol in the tracking area and were in foveal view). We refer to this as VO. Four more of the visual tasks were located to the right of the tracking task at the following visual angles: 7.4 degrees (VH1), 15 degrees (VH2), 32.5 degrees (VH3), and 46.2 degrees (VH4) (see Figure 2). The visual angles were measured from the center of each of the display boxes.

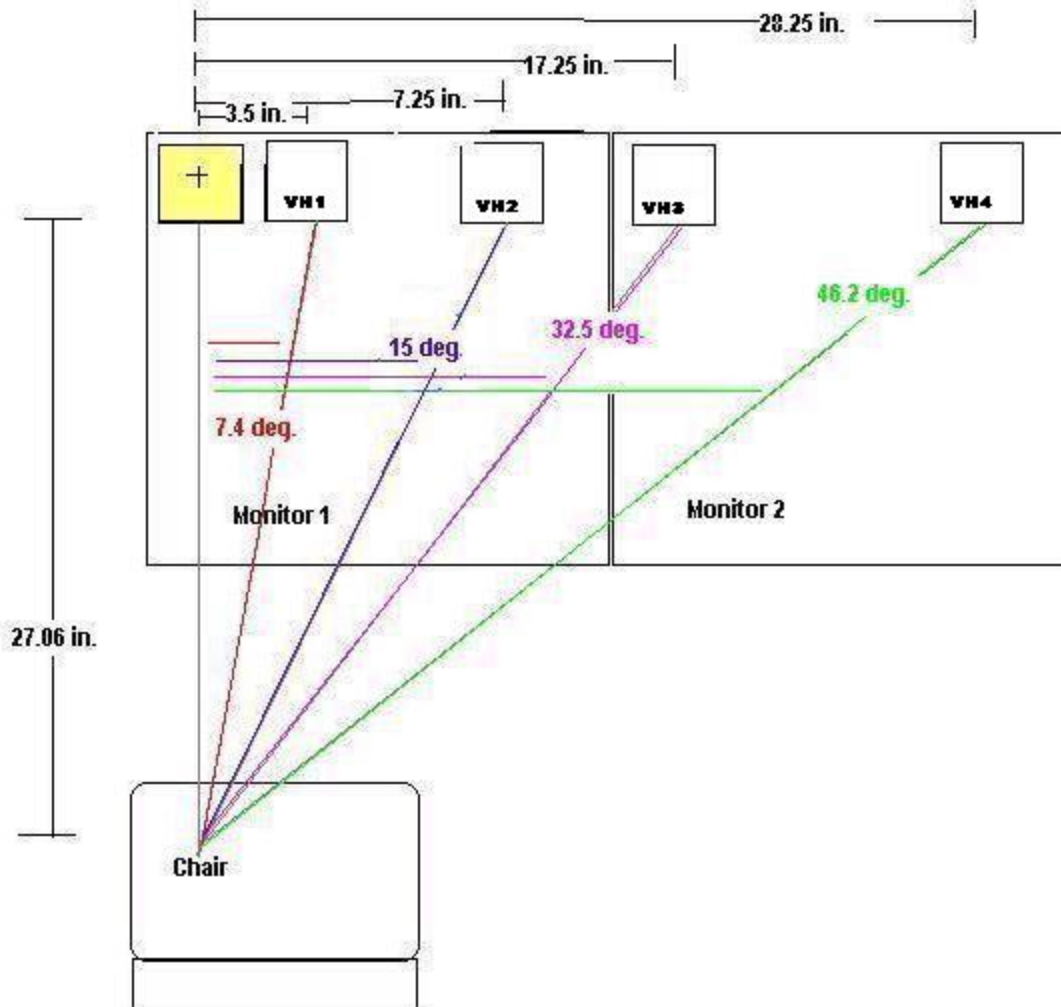


Figure 2. The horizontal secondary tasks. The condition labels are shown within each box.

Two additional visual configurations were located below the tracking task (see Figure 1) at the same vertical angles as the two horizontal visual tasks on the left monitor. Therefore, there was one visual task located 7.4 degrees below the tracking area (VV1) and one located 15 degrees below (VV2).

The participants heard the auditory side task over the computer speakers playing digitized voice messages. They were only allowed to hear the digits once and then make their response. The 4-digit numbers lasted an average of 1.26 seconds (with a range of 1.16s – 1.38s); the 7-digit numbers lasted an average of 2.39 seconds (with a range of 2.25s – 2.56s); and the 10-digit numbers lasted an average of 3.41 seconds (with a range of 3.30s – 3.63s).

Subjects

Thirty six undergraduate and graduate students at the University of Illinois at Champaign-Urbana took part in the experiment. The subjects' ages ranged from 18 to 35. There

were 11 males and 26 females. Subjects were paid \$7 for their participation, which normally took 35-45 minutes. All of the subjects finished the experiment.

Procedure

Each experimental trial consisted of participants having to manipulate the joystick in order to keep the green cursor as close to the '+' symbol (or center of the tracking area) as possible. While doing this, they were also expected to read or listen to a set of digits and repeat them verbally back to the experimenter as soon as they were perceived. When the participant initiated the voice response, he or she pressed the joystick trigger. The instructions clearly emphasized that the participant must precisely synchronize the key-press with the initiation of their verbal response. Participants were reminded of this procedure after each block and upon any failure to accurately press the joystick trigger during a response. The experimenter pushed one key when the response was finished and another key to record accuracy.

Participants were asked to attend equally to the tracking and digit tasks. Each participant was given one practice block beforehand, which presented 2 phone numbers of the various lengths (4, 7, 10) in each of the eight different configurations combined with the tracking task.

Data were recorded when A) there was no side task activity (baseline), B) the stimulus first appeared, C) the participant pressed the trigger to begin his or her response, and D) the experimenter pushed the key to mark the end of the response. The data were stored separately for the 4-, 7-, and 10-digit events. The RMS error, Reaction Time (RT), Accuracy, and Stick Velocity were stored in separate bins for the baseline period, the RT period (B-C) and the speech period (C-D). The measurement of RT was initiated at the onset of the visual side task digit string, or at the termination of the auditory string.

Design

The nine trials were presented in a blocked configuration and were counterbalanced within the block to negate order effects. Within each of the nine trials, the digits strings were randomized over digit length. A within-subjects design was employed to minimize subject effect and to decrease the number of required subjects.

Results

In the following analyses, the results are broken down in terms of side task performance (RT and speech time) as well as tracking performance (control stick velocity and RMS error) for each of the side task intervals (i.e., prior to and during verbal response). Only one significant effect was observed on accuracy, which will be described below. Thus in all other cases, we can be confident that latency effects did not reflect a speed accuracy tradeoff. We analyze (in separate ANOVAs) the auditory effect, comparing auditory (A) presentation with adjacent (VH1); the HUD effect, comparing VH1 with overlay (VH0); the near separation effect, comparing VH1, VH2, VV1, and VV2; and the eccentricity effect, comparing VH2, VH3, and VH4.

1. Auditory Effect (VH1 vs. A)

1.1 Response time. As shown in Figure R1, RTs were 240 msec faster to the auditory side task than to the visual side task onset ($F(1, 34) = 23.7; p < .01$). The main effect of side task load revealed that longer stimulus strings took longer to initiate ($F(2, 68) = 28.94, p < .01$). More specifically, it took 200 msec longer to initiate the longest message, relative to the shortest. We assume that this effect was due to the fact that it takes longer to initiate longer or more complex responses (Wickens & Hollands, 2000). Finally, the interaction between load and modality indicated that the greatest auditory speed advantage (370 msec) was realized with the shortest, 4 digit stimulus ($F(2, 68)$ interaction = 7.53; $p < .01$). Note that it is possible to argue that the auditory advantage was an artifact of a "head start" in timing, since the RT clock started at the end of the voice message. If subjects had actually started to process this voice message before its termination, then the recorded RT in the auditory condition would be an underestimation of the true processing time. We do not believe that this was the case, since such an argument would suggest that there should be more of an advantage for longer digit strings. However, in fact, the opposite effect was observed, as seen in the form of the interaction.

1.2 Speech time. As shown in Figure R2, the time required to speak the digit response was longer when the digits had been presented auditorially, rather than visually ($F(1, 34) = 14.15; p < .01$), particularly at the larger loads (longer digit string; interaction, $F(2, 68) = 20.60; p < .01$). Load naturally increased the speaking time ($F(2, 68) = 1011.08; p < .01$), at a rate of approximately 0.4 sec/digit. The interaction between load and modality can be interpreted as interference within the verbal code between speaking and rehearsing within the RT task (i.e., within-task code interference). The fact that this auditory-rehearsal cost is not evident till the load reaches 7 digits, suggests that it is rehearsal based. That is, the 4-digit load does not exceed the capacity of working memory, and hence does not need to be rehearsed. This speech time effect is also supported by response accuracy, and was the only variable to influence accuracy in any substantial way.

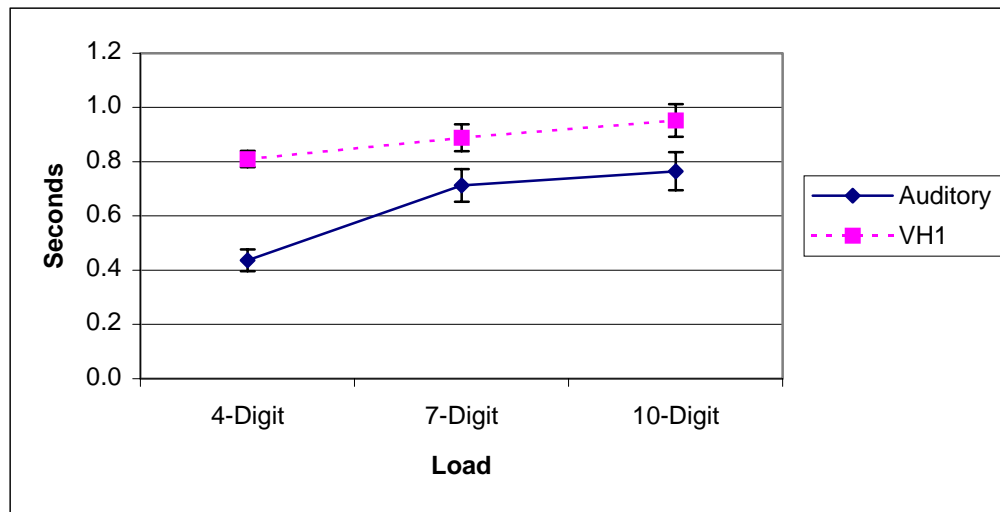


Figure R1. Reaction time to the side task by secondary task load and modality. Error bars in this and subsequent figures represent one standard error.

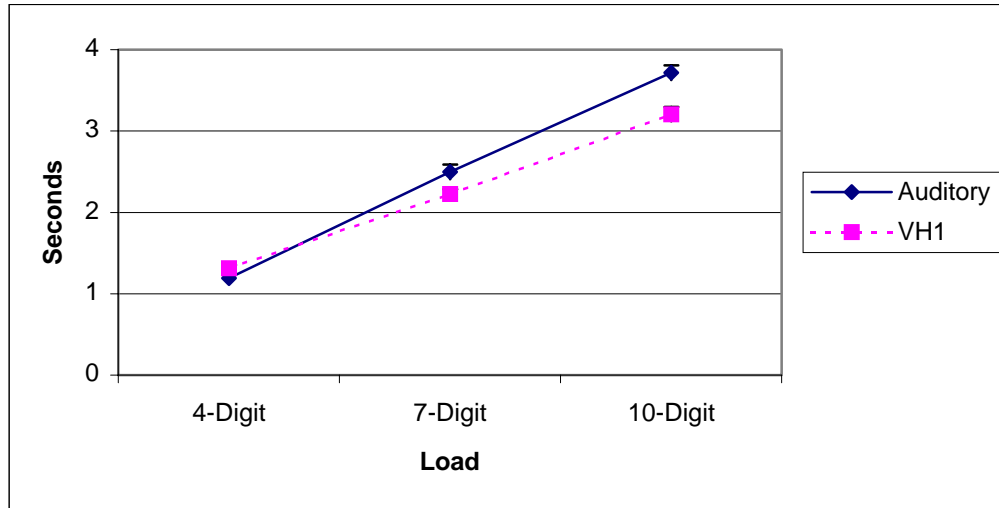


Figure R2. Speech time to the side task by secondary task load and modality.

1.3 Tracking during the RT interval. No effect of the auditory presentation was observed during the RT period, in either tracking behavior (stick velocity) or consequent performance (RMS error).

1.4 Tracking behavior during speech interval behavior (stick velocity). As seen in Figure R3, the response velocity was increased by auditory presentation during the speech period ($F(1, 35) = 4.64$; $p = .038$). (Not shown in Figure 3 is the response velocity observed during pure tracking-only intervals which was a value of 10.7 on auditory trials and 11.3 on visual (VH1) trials.) Increasing load produced an equivalent increase in control stick velocity for both the auditory and visual condition ($F(2, 70) = 5.54$; $p < .01$). Thus the modality effect did not appear to grow with increasing side task load (interaction $F(2, 70) = 1.94$, $p > .10$), and therefore would seem to be associated with the initiation of the voice response, rather than its continuing articulation.

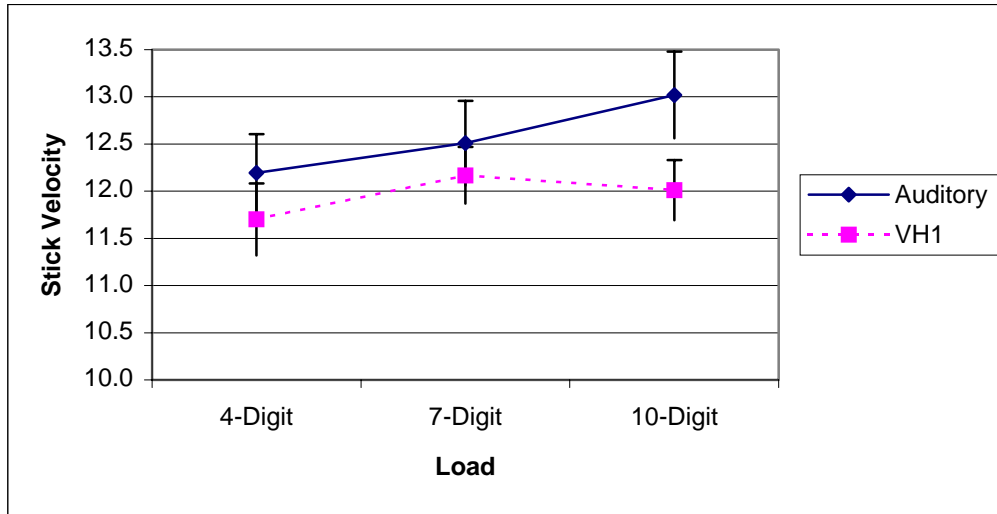


Figure R3. Stick velocity during the speech interval by secondary task load and modality.

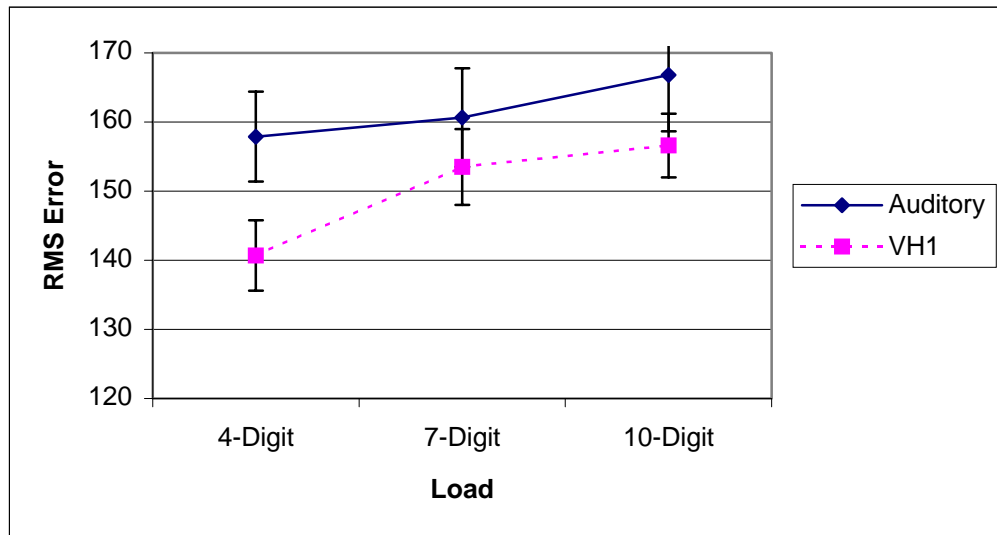


Figure R4. RMS error during the speech interval by secondary task load and modality.

1.5 Tracking performance during speech interval (RMS Error). As seen in Figure R4, the auditory presentation, and its accompanying increase in response velocity, actually produced a significant 6.83% increase in RMS error compared to adjacent visual presentation ($F(1, 35) = 8.83$; $p = .01$). This pattern was also reflected in the single-dual decrement, since error in the tracking only blocks with the auditory task was 151, and with the visual (VH1) task was 147. Side task load did have an influence on tracking error ($F(2, 70) = 5.79$; $p < .01$), suggesting the role of within stage (response) interference between tasks. That is, executing (speaking) longer responses disrupted the response (control) activity of tracking, producing greater RMS error. The auditory cost did not increase with greater load (interaction effect: $F(2, 70) = 1.06$; $p = .35$), so this

cost was probably not related to the code interference mechanism that caused the increased auditory cost in response time discussed in 1.2 and Figure R2 (nor should it be related to that, since that cost was within-task verbal resource interference, and the tracking task uses spatial resources). The fact that this auditory cost in tracking error shown in Figure R4 was unrelated to load, in parallel with the corresponding absence of load relation for the auditory effect on stick velocity (section 1.4 and Figure R3) suggests that this tracking error increase was related to extra activity, induced by the auditory presentation, at the **beginning** of the speech response interval (and therefore unrelated to its length), activity which was somehow counterproductive. This counterproductive activity could be conceived of as a sort of “startle” reaction, as attention is discretely switched to the source of auditory input.

1.6 In summarizing the effects of display modality on tracking behavior and performance, the overall performance data appear to be consistent with a form of “onset preemption”. That is, the consequence of using an auditory display are to provide an advantage in dual task RT to the side task, which is greatest for short messages, and a subsequent cost to tracking error. This cost is measured in the interval after the voice response has started, and presumably is a consequence of whatever it was that added velocity to the control stick activity. Thus it should be noted that both the “auditory effect” and the “load effect” are associated with more response activity, and with greater, rather than less error, a pattern of effects that is not consistent with a single channel view of auditory preemption (in which tracking would be assumed to be halted by the delivery of auditory information). This close linkage of response velocity and tracking error is shown in Figure R5, which cross plots the two measures across the 6 conditions.

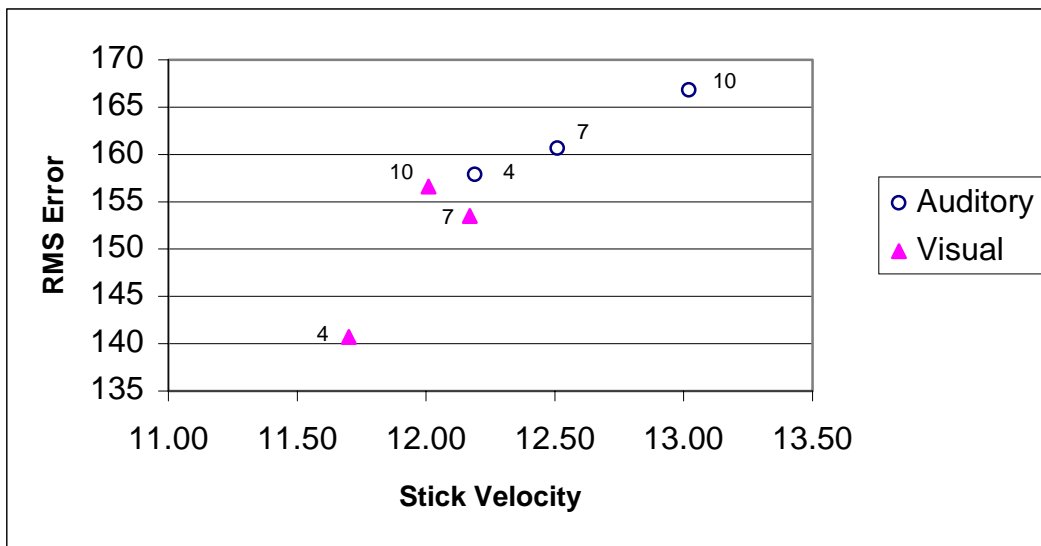


Figure R5. Cross plot of RMS error and stick velocity. Numbers in the graph represent the side task load.

The specific cause of the increase in response velocity, both resulting from the change in modality, and from the increase in side task load remains somewhat unclear. Presumably it relates to some form of confusion and crosstalk (Fracker & Wickens, 1989) within the response stage, but operating across response modalities, a crosstalk that is counterproductive to dual task tracking performance.

2. **Overlay Effect (Adjacent (VH1) vs. Overlay(VH0))**

2.1 RT. There was an effect of increasing side task load on the time to initiate the response ($F(2, 70) = 14.56; p < .01$). This did not interact with display location, nor was the main effect of location significant.

2.2 Speech time. In addition to the large effect of side task load on speech time, described in section 1, There was a significant .06 sec increase in the time to articulate overlaid digits, relative to adjacent ones, ($F(1, 35) = 5.58; p = .02$), an effect that can be clearly associated with clutter.

2.3 Tracking during the RT interval. Overlay reduced the amount of control velocity ($F; 1,35 = 6.01; p < .02$) during the RT interval.

2.4 Tracking during the speech interval. Overlay decreased stick velocity ($F; 2,70 = 3.2; p = .05$); and increased RMS error ($F; 2,70 = 3.84; p = .03$) while the subject was articulating the response. Participants apparently slowed their stick movement to make the overlaid text more readable, and their tracking error suffered as a result.

3. **Separation Effect (Near)**

We divide our treatment of separation effects into two categories. One analysis, which we label “separation near”, examines only scanning within the “eye field”; that is, at separations of between 7 VH1 and VH2 and 15 degrees (VH2 and VV2), and examines the implications of both vertical and horizontal separation. Then we will describe an analysis of the effects of “far separation” or **eccentricity**, beyond 15 degrees, when the eye field and the head field are engaged, but only in the horizontal axis.

3.1 RT: As shown in Figure R6, response times were about 0.10 sec longer with greater eccentricity ($F(1, 33) = 12.39; p < .01$), a cost that is presumably related to a greater failure to immediately notice stimulus onsets at the more separated locations. While there was no effect of direction on RT, there was a marginally significant direction by distance interaction ($F(1, 33) = 3.59; p = .07$) that suggests that the vertical separation cost (VV, moving the display downward) was greater than the horizontal separation cost (VH, moving it to the side). This interaction suggests that noticing discrete events is more proficient in the right than in the bottom peripheral visual field, a finding compatible with Previc’s model of the 3D space perception. The interaction also could reflect the fact that monitoring scans, to check whether a side task stimulus has appeared, are made more frequently laterally than vertically. In the latter case, we would expect the “vertical eccentricity cost” to be equivalent if we had instead displaced the display to the left, or upward, manipulations that were not made in the current experiment.

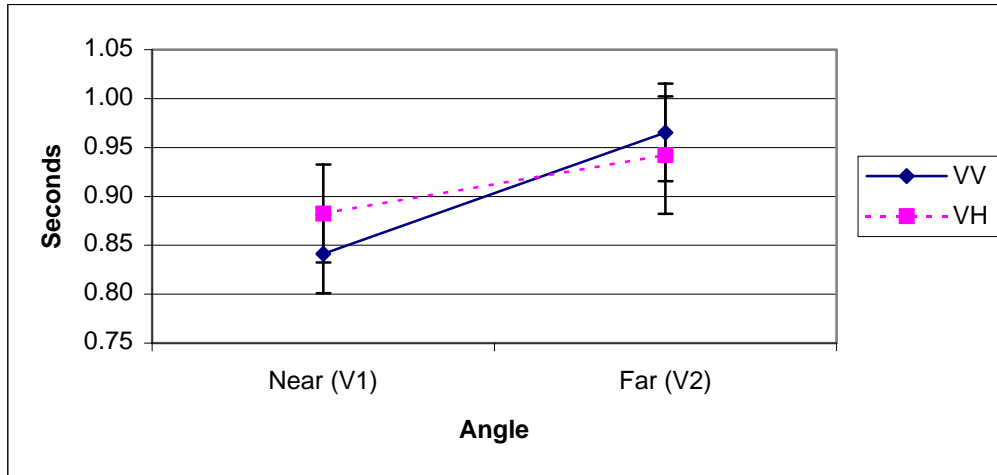


Figure R6. Reaction time to the side task by eccentricity (near – 7.4 degrees, far – 15 degrees) and display direction (horizontal vs. vertical).

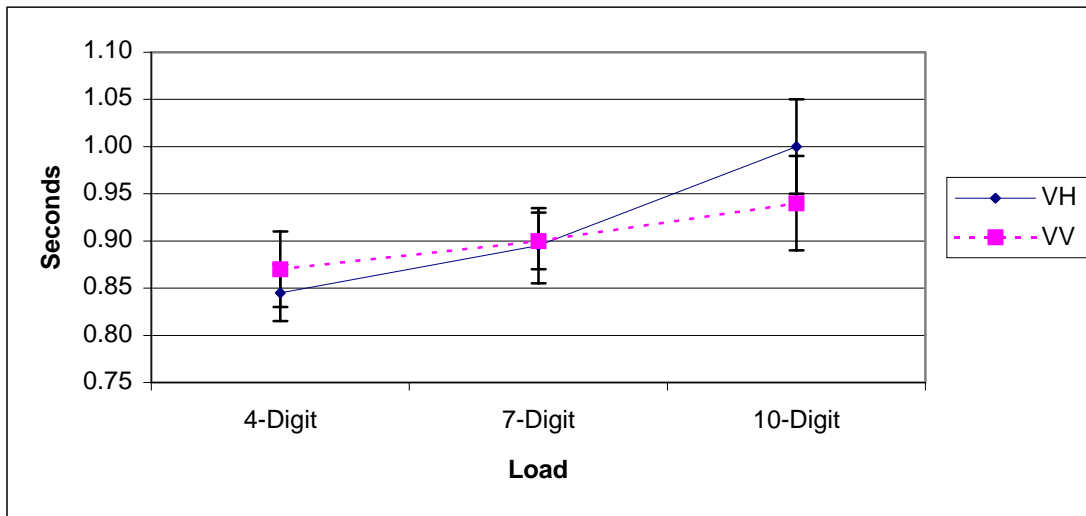


Figure R7. Reaction time to the side task by secondary task load and display direction (horizontal vs. vertical), summed across eccentricities.

As shown in Figure R7, there was a significant delay in initiating the response with greater side task load ($F(2, 66) = 10.86; p < .01$) and a significant Direction x Load interaction ($F(2, 66) = 3.72; p = .03$). This latter effect described the greater impact of increasing load on horizontal displacements than on vertical displacements, independent of the degree of eccentricity.

3.2 Speech time. As shown in Figure R8, there was a large effect of separation angle on the time required to articulate the response ($F(1, 33) = 27.35; p < .01$). There was no direction effect, nor any interaction with direction. The very large effect of load ($F(2, 66)$

=764.16; $p < .01$) described above was fully expected, since it takes longer to say more digits. Load interacted with angle ($F(2, 66) = 19.28$; $p < .01$), such that the load cost is greater at wider eccentricities (or alternatively, the scanning cost is greater at higher loads). This finding would suggest that, with longer digit strings, and 15° eccentricity subjects occasionally would scan back to the tracking task, and such checking increased the time to read and speak the longer digit strings.

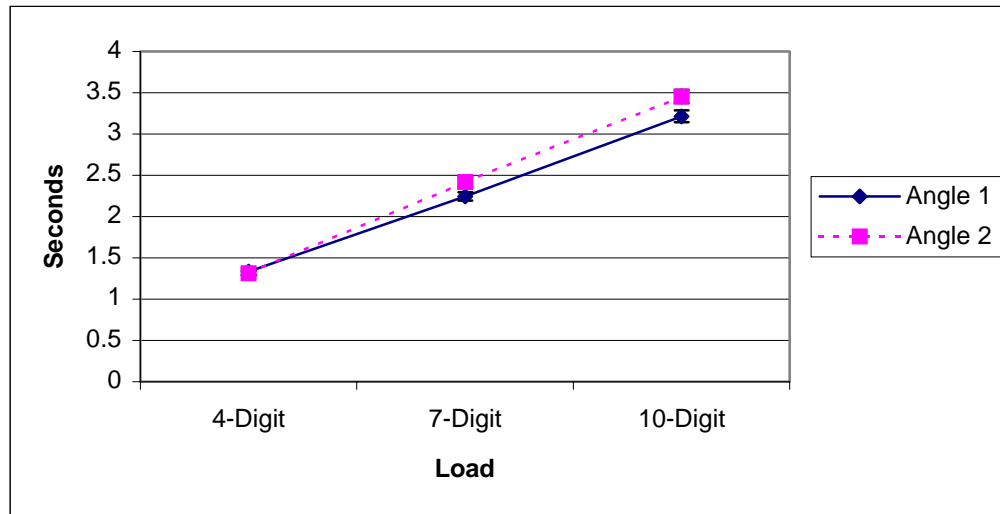


Figure R8. Reaction time to the side task during the speech interval by secondary task load and eccentricity (near (Angle 1 – VH1, VV1) vs. far (Angle 2 – VH2, VV2)), summed across display direction.

3.3 Tracking behavior in the RT interval: stick velocity. There was no effect of angle or direction, reinforcing the conclusion that the abovementioned prompt RT delay (due to eccentricity) was simply a delay in noticing side task stimulus onset. That is, during the delay period, the subjects went on tracking just as they had in the baseline period prior to stimulus onset.

3.4 Tracking performance in the RT interval: RMS error. Consistent with the absence of effects on behavior, there were no reliable effects on tracking error during the prompt period either. There was however a non significant trend ($F(1, 34) = 2.68$; $p = .11$) for more error at greater eccentricity, and when the digit display was displaced vertically ($F(1, 34) = 2.72$; $p = .11$), consistent with the hypothesis that on some trials subject might have scanned to the digit string before starting their response, and after scanning, had better tracking when the tracking cursor was in the left visual field than in the upper visual field, a finding consistent with Previc’s model of 3D visual space.

3.5 Tracking behavior during speech: stick velocity. There were no significant effects on response velocity during the response period. Thus it appears that subjects were investing the same amount of effort into the tracking task, independent of its location, or the load imposed by the RT task.

3.6 Tracking performance during speech: RMS error. There was a large 17% eccentricity cost on tracking error ($F(1, 34) = 71.0, p < .01$), a cost which, in the absence of any change in control stick velocity (section 3.5), we can attribute to the degraded quality of peripheral vision at greater eccentricities. As shown in Figure R9, there was also a greater cost of vertical than lateral displacement (main effect: $F(1, 34) = 9.37; p < .01$) a finding consistent again with Previc's hypothesis, that tracking in the upper periphery is poorer than tracking in the left periphery (right hemisphere).

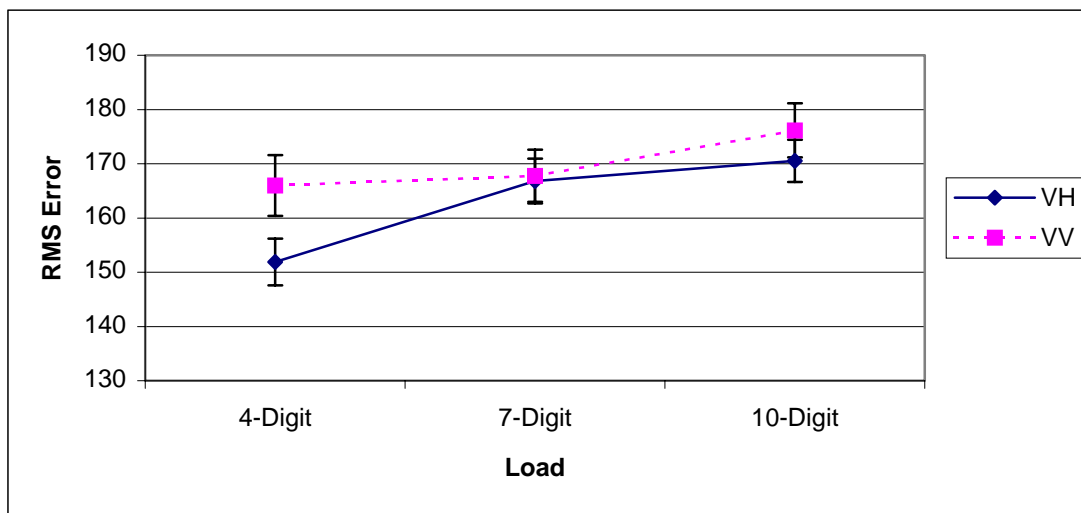


Figure R9. RMS error during the speech interval by secondary task load and display direction (horizontal vs. vertical), summed across eccentricities.

As seen in Figure R9, there was also an increasing cost to tracking error with greater load ($F(2, 68) = 11.46; p < .01$) and a significant load X direction interaction ($F(2, 68) = 5.61, p = .01$), indicating that there was a greater horizontal advantage at smaller loads. The pattern of this interaction suggests that with smaller loads, the subject stays fixated on the side task until the digits are completely read, and thus relies entirely on peripheral vision to track during the interval. Thus we see the directional asymmetry associated with Previc's model (greater cost with vertical than lateral displacement) at small loads. However at larger loads, subjects may occasionally scan back to the tracking task (thus causing the increased delay in speaking the response, described in section 3.2), restoring it to peripheral vision, where it would be unaffected by the Previc asymmetry. That is, at larger loads, tracking error will reflect a mixture of foveal and peripheral tracking. At smaller loads, it reflects only peripheral tracking, where the directional asymmetry operates.

3.7 Conclusion: Near separation. In conclusion, there is evidence that separation (eccentricity) within the eye field has a degrading effect in both tracking performance and response time, an effect that is slightly larger for the latter (17%) than the former (12%). There was also some evidence for greater costs of vertical (downward) separation than horizontal (rightward) separation, more consistently seen in tracking error than in side task measures.

4. Eccentricity Effect

A comparison of regression lines between all four dependent variables reveals the overall effect of eccentricity to be borne most heavily on tracking error, as we describe below in analyses that incorporate only the three most eccentric visual angles of 15 degrees, 32.5 degrees and 46 degrees.

4.1 RT. As shown in Figure R10, eccentricity had a monotonic cost on the time to initiate the response ($F(2, 68) = 17.38; p < .01$). There was a significant effect of load, but this can only be interpreted within the context of the interaction between load and eccentricity ($F(4, 136) = 2.46; p = .049$). The cost of eccentricity appears to be related to the failure to notice the more eccentric stimuli, rather than to any conscious “waiting” to deal with it, since the cost is actually smaller with larger load. That is, at wide eccentricity, when the stimulus sources are no longer in the same eye-field, but now lie within the head field, it appears as if the subject switches attention (and scans), and then fully responds, whereas at the smaller eccentricities the subject may wait longer to begin the longer (7 and 10 digit) responses.

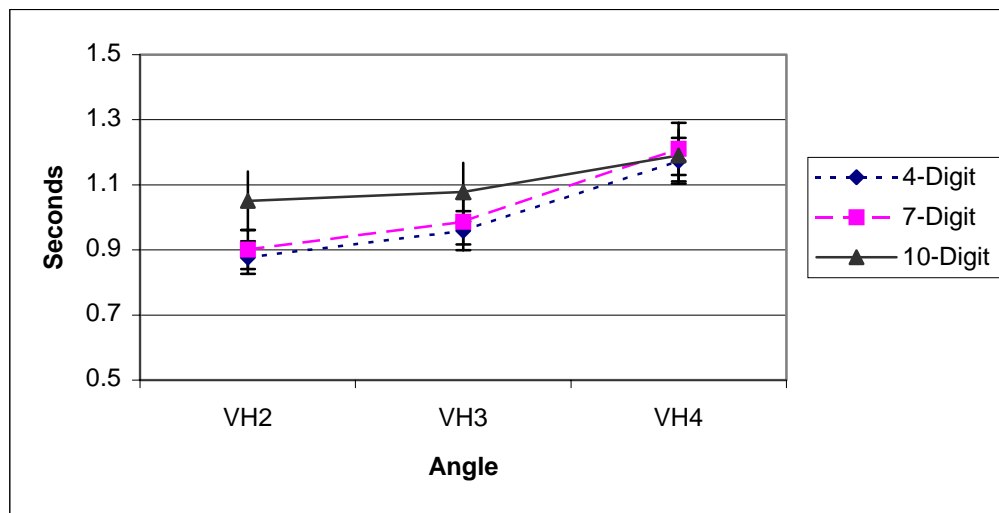


Figure R10. Reaction time to the side task by eccentricity (horizontal direction only) and secondary task load.

4.2 Speech time. There was a cost of wider eccentricity in the time it took subjects to complete the response ($F(2, 68) = 18.69; p < .01$; an increase in 0.20 sec from near to far). As we have seen elsewhere, there was also a large cost of load ($F(2, 68) = 540.42; p < .01$), which was of approximately the same magnitude as the load cost described within the eye-field, in section 3 (about 0.40sec /digit). As shown in Figure R11, there was a small, but significant interaction of load and eccentricity ($F(4, 136) = 9.04; p < .01$), suggesting that the time increase to speak the longest (10 digit) string is amplified slightly when it was presented at the widest eccentricity, a consequence probably of more glances back to the tracking task at this wide eccentricity with the longest digit strings.

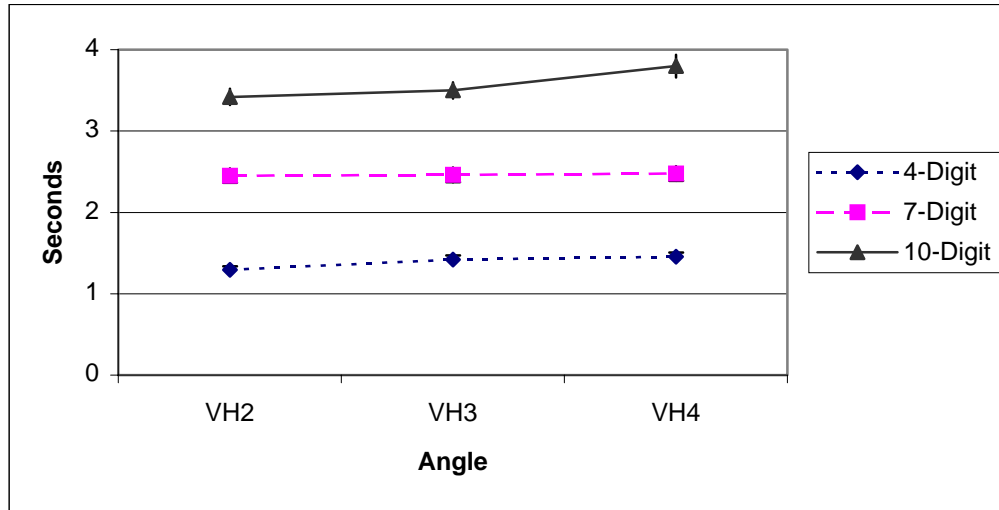


Figure R11. Speech time to the side task by eccentricity (horizontal direction only) and secondary task load.

4.3 Tracking behavior during the RT interval: stick velocity. During the RT interval, there was a slight reduction in tracking activity at greater eccentricity ($F(2, 68) = 3.13$; $p = .05$). Load did not affect the tracking velocity at any eccentricity. Although there was a significant load X eccentricity interaction ($F(4, 136) = 5.99$; $p < .01$), this did not appear to be monotonic, and was not easily interpretable.

4.4 Tracking performance during the RT interval: RMS error. Increased eccentricity, and the reduced response velocity resulting, clearly degraded tracking error ($F(2, 68) = 14.84$; $p < .01$). As with response velocity, so there was no effect of load on tracking error at these eccentric locations during the RT period ($F(2, 68) = 0.60$; $p = .55$); Also consistent with response velocity, while there was a load X eccentricity interaction (marginally significant), it was neither monotonic, nor reflective of the variance in response velocity, and hence no effort is made to interpret its meaning. Thus we interpret the collective influences of eccentricity within the response time interval, as suggesting that greater eccentricity imposes a greater time to notice the side task digit string and hence switch attention to it (independent of its length). The time after the switch has occurred, but before the articulation has begun, is reflected in lower tracking activity and higher error.

4.5 Tracking behavior during speech: stick velocity. Control stick velocity while the subject is speaking decreases monotonically with increasing eccentricity ($F(2, 68) = 6.79$; $p < .01$), independent of the load ($F(4, 136)$ interaction = .446; $p = .776$), while load itself has no effect on response activity ($F(2, 68) = .858$; $p = .428$).

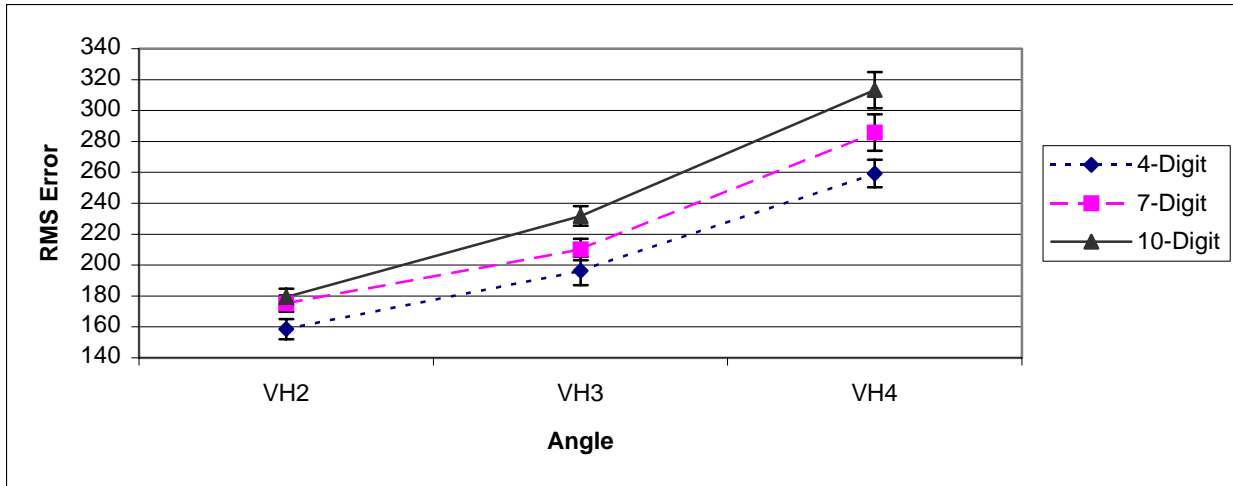


Figure R12. RMS error during the speech interval by eccentricity (horizontal direction only) and secondary task load.

4.6 Tracking performance during speech: RMS error. As shown in Figure R12, the reduction in stick activity associated with the greater eccentricity described in section 4.5 has an expected effect on increasing tracking error ($F(2, 68) = 156.82$; $p < .01$), and this increase is huge (63.9%) and is nearly additive ($F(4, 136)$ interaction = 2.48; $p = .05$) with the large effect of load (21.5% increase from 4 to 10 digits; $F(2, 68) = 28.72$; $p < .01$). Thus, these effects at greater eccentricity provide good evidence for a resource allocation interpretation, although not a single channel interpretation, since the stick velocity remains at a value far above 0.

4.7 In summarizing the effects of eccentricity, comparing tracking with the side task, we see that the side task appears to be buffered from the effects of wide eccentricity, relative to tracking. Stated another way, the non-linear information access cost function proposed by Wickens (1993) and shown in Figure 1, appears to better characterize tracking than performance of the side task although Figure R10 does suggest some non-linearity. In contrast, the costs of increased load appear to be fairly equally borne by tracking and by the side task. Finally, it appears that the load effects are generally unrelated to (and do not much interact with) the eccentricity effects, as if both effects have somewhat different loci within the information processing system, the former influencing perception, and the latter influencing the selection and execution of action. This decoupling of perception from response is consistent with a stage-defined distinction in multiple processing resources (Wickens, 2002), to be discussed in the following section.

Discussion

The current experiment was designed to provide a comparative evaluation of two solutions designed to address issues of visual overload in the cockpit or driver cab: auditory presentation and superimposition. To do so we had participants perform a tracking task which could represent the information processing demands of either flying or driving in turbulence, with a concurrent “in-vehicle task” which we refer to as the side task. The side task, remembering (auditory only condition) and repeating digits, was designed to be sufficiently simple, so that its processing demands could be well modeled, yet of sufficient realism so as to generalize to either the flight environment, in which pilots must retain digital information regarding radio frequencies or navigational trajectories, or to the automobile, where such information simulates telephone numbers that may need to be voice dialed on a cellular phone. We examined how much each task was disrupted by the presence of the other, and in particular, how these dual task interference measures were amplified or reduced by task parameters. We use tracking response velocity as a diagnostic measure to assess the degree of the subject’s engagement in the tracking task; a measure that plausibly drops to zero when the subject “stops tracking” (i.e., removes hands from the joystick). The results will be discussed first with regard to their implications for the separate effects of modality, visual overlay, and visual separation and then for their broader implications for the view and models of time-sharing.

5.1 Auditory Versus Visual Interference

In the introduction, several mechanisms were described that could account for differences between aV and vV task performance. The first of these, and the most obvious, relates to the potential advantage of an aV combination, when compared with a vV combination that involves widely separated sources of visual information for the two tasks. While the effect of such separation will be examined in detail in section 5.4, it is sufficient to note here that there were obvious advantages to delivering auditory information, relative to the widest eccentricities of the visual displays. Tracking error for example was reduced by such auditory delivery from 290 units to 165 units, while response times decreased from well over 1 second for the widely separated visual stimulus, to approximately 0.70 seconds for the auditory stimulus. While such differences can be accounted for by pure “structural” mechanisms of visual scanning and poor peripheral vision, they do have important operational implications, when the alternative visual display is one, captured by VH4, that is well removed from the center of interest outside the cockpit or driver cab. Even at 15° of separation (V2) there was a roughly 0.25 sec advantage in auditory RT, and a 10% reduction in tracking error.

More interesting from a theoretical standpoint are the consequences of aV versus vV comparisons with smaller separations in the vV case. Here we chose a visual angle of 7.5 degrees between the center of the tracking task, and the center of the visual stimulus, as a minimum angle that would still allow the digits to be large enough to be easily read, and would prevent them from ever overlapping with movement of the tracking cursor in its largest expected rightward excursion (see Figure M2). In this comparison, the evidence for separate perceptually-defined resources was muted. While the side task performance clearly supported aV relative to vV interfaces, and did so particularly with short messages, such evidence, as we have noted, is equally consistent with a preemption model. Examination of the tracking data appeared to support preemption, rather than multiple resources, since tracking error was **more** disrupted by

the auditory than the visual delivery of information (see Figures R3 and R4). The fact that this auditory-related disruption lessens, rather than increases with longer responses appears to implicate onset preemption, rather than strategic preemption, since existence of strategic preemption would suggest that the participants would stop tracking for a longer time, with longer messages, in order to “dump” their working memory for the voice message.

Finally, in interpreting these results, it is interesting to note that both the modality and the load influence on tracking performance, were related to a distinct **increase**, rather than a decrease in tracking behavior (stick velocity). While in both cases this increase appears to be directly associated with poorer tracking (Figure R5), we also associate the increase with slightly different phenomena in the two cases. In the case of the auditory onset increase, we infer the cause to be some abrupt change in joystick control, associated with the disruptive appearance of the auditory message. The fact that this change does not produce an increase in tracking error till the speech interval, is consistent with the general lag between tracking stick behavior, and subsequent error (increase or reduction), that is associated with the first order tracking task employed here (Wickens, 1986; Tsang, Shaner, & Vidulich, 1995).

In contrast, we infer that the increase in velocity associated with the longer digit responses may reflect a “crosstalk” mechanism, such as that observed by Fracker and Wickens (1989) whereby responses intended for one task are inadvertently delivered to the other. It remains somewhat surprising that this effect, previously associated only with dual manual tasks (see Wickens & Liu, 1988), was observed here in cross-modality control. However most prior findings of the absence of crosstalk effects in cross-modality time sharing, have used voice responses that are simple single syllable response, rather than the more complex strings employed here.

It is of course appropriate to ask why the benefits of separate modality-defined resources were not more in evidence here, given their emergence in other more basic laboratory studies (e.g., Schumacker et al, 2001; Treisman & Davies, 1973). One plausible explanation, is that where there is a clear asymmetry between the discrete and the continuous task (an asymmetry present here, but absent in the two studies described above), this may naturally invite the auditory onset preemption effect, as observed so frequently in the other studies of this sort reviewed by Wickens and Liu (1988). In this case, it is of interest to determine the extent to which training, or even simple instructions in dual task attention management (Gopher, 1992; Tsang & Wickens, 1988) could be employed to overcome the preemption effect, and allow the benefits of multiple resources to emerge.

5.2 Information Overlay

The effects of information overlay were examined by comparing the adjacent with the overlay position, and these effects were fairly straightforward, reflecting the tradeoff between clutter and scanning that has been observed elsewhere (see Wickens, Ververs, & Fadden, in press, for a review). The results indicated that overlaying digits on a moving cursor did not affect the time required to detect them (i.e., the scan reduction offset the costs of clutter), but did prolong the time required to read those digits. Readability during the RT interval was apparently achieved by slowing movement of the overlaying cursor, an action which had small, but significant negative consequences on the subsequent tracking error. Of course the current study

did not examine the one critical performance cost that is sometimes associated with HUD overlay: the failure to detect **unexpected**, low salient events in the far domain (Wickens et al, in press; Fadden, Ververs, & Wickens, 1998). It should also be noted here that performance on the adjacent position was in all respects equal or superior to the overlay position. That is, stated in other terms, there was no cost of spatial separation here at small angles, thereby validating the preferred location of automobile HUDs, viewable in front of the hood, just below the roadway.

5.3 Visual Channel Separation

The impact of separating the tracking and digit tasks was examined in two separate analyses. One analysis only concerned the effects of peripheral vision, or eye scanning, by constraining the separation to be well within the so-called “eye-field”, estimated to be less than 20 degrees (Bahill et al., 1975; Previc, 1998). With these constraints we were also able to examine the separate effects of lateral and vertical separation. The other analysis, in the horizontal plane only, examined the changes in interference resulting as the head field was entered, and at extreme levels of separation, at which peripheral vision would seem to allow minimal perceptual processing.

In the first analysis, examining eccentricity and direction within the eye field, the most robust finding was that the increase in separation from 7 degrees to 15 degrees in either direction, prolonged the time to respond (by 0.10 sec, Figure R6), as well as the time to speak the response (although the latter effect only was observed at longer stimulus loads, Figure R8). Both of these effects presumably reflected the costs of occasionally removing the digit display from foveal vision. A visual saccade would then need to be initiated, upon noticing the stimulus onset, before the response could begin (explaining the RT effect), and, with longer digit strings on the screen, subjects presumably made a brief saccade back to the tracking cursor while a response of greater length was being executed. This latter “tracking checking scan” would explain the effect of eccentricity on speech time for the 7 and 10 digit strings.

The wider eccentricity of the 15 degree separation also relegated the tracking cursor to the periphery, during the time that the digits received the focus of visual attention. This displacement caused the tracking error to be perceived with less resolution, thereby degrading the precision of correction, an effect of peripheral tracking that has been well documented in the literature (see Wickens, 1986 for a summary). However this displacement does not appear to lead to any abandonment or allocation of resources away from tracking, as the stick control velocity is unaffected by eccentricity, consistent with the analysis of peripheral tracking carried out by Allen, Clement, and Jex (1970).

Less salient than the eccentricity effect, but of considerable theoretical interest are the manifestations of a direction effect. Previc (1998) has offered a theory of visual systems in 3D space perception, that proffers an advantage to the lower and left visual fields for motion perception, and to the upper and right visual fields for detection of fine detail and reading. The lateral asymmetry is clearly related to differences in hemispheric processing of verbal versus spatial information, and such asymmetry has been reflected in other studies of multiple task performance between verbal and spatial tasks (Wickens, Sandry, & Hightower, 1982; Wickens & Sandry, 1982; Wickens, Vidulich, & Sandry-Garza, 1984). The vertical asymmetry is more associated with the lower visual field’s role in processing the ambient motion of walking and

manual manipulation (the hands and terrain flow are more often viewed in the lower visual field), and the upper visual field's role in seeing fine (often distant) detail (Previc, 1998). Less data are available to support the viability of this latter distinction (e.g., Sochacki & Wickens, 1997).

The data of the present experiment are consistent with the distinctions made by Previc, although it is to be noted that only half of the conditions necessary to provide a full test of the theory were included. That is, we did not displace the digits upward nor leftward. Our reasoning is that, in either the cockpit or the cab (with a left seat driver), it is more likely that side task information would be displaced downward or rightward, than in the other directions. With this qualification in mind, we note that RT was faster to digits in the right periphery than in the lower periphery, and that tracking error was increased more by an eccentric displacement of the digits downward than rightward, a differential cost measured in both the RT period (a non-significant, $p = 0.11$ trend), and in the speech period. This latter disruption of tracking error was greatest for shorter speech responses. With longer digit strings, requiring longer to speak, it was inferred that subjects might have scanned back to the tracking display in mid interval. Such scanning would restore tracking momentarily to foveal vision, where laterality issues would not be relevant.

The effects of wider eccentricity, moving from the eye field at 15 degrees, into the head field, at 32 and particularly, 45 degrees, had a modest effect on both the response time, reflecting the delay in noticing the stimulus onset (Figure R10), and the speech time (Figure R11), reflecting some prolongation required to scan back to the tracking task, an action taken primarily with the longest digit string responses. However in general the effects of load on the time to initiate the response continued to be small, just as they had been at the lower eccentricity values. The RT cost from VH2 to VH4 was only 0.20 seconds (approximately a 20% increase), and of equivalent magnitude for the speech cost. There was little evidence in the side task data for the pattern of non-linearity across eccentricity, associated with the model in Figure 1.

In contrast, tracking performance showed both a more pronounced effect of increased eccentricity (a roughly 60% increase, Figure R12), and a greater tendency to reflect the non-linear trend, particularly during the speech portion of the side task. During both periods (RT and speech time), the increase in error was directly associated with a decrease in response velocity, suggesting that at these wide eccentricities there is a true "resource allocation" effect, that was absent in the closer separations discussed above. That is, participants "tracked less" while the discrete task was being processed, a behavioral change that sacrificed their performance on that task. The fact that the non-linearity was observed in tracking, and not (or less so) in the side task may be accounted for by assuming that, when the side task was more widely separated, subjects chose to stay with it, until it was completed, rather than engaging in a time and effort consuming head movement in the midst. Such an attention movement was less inhibited when its cost was only that of a visual scan and not a head rotation, at separations of 7, 15, or possibly even 32 degrees.

5.4 HUD Versus Auditory: The Best Solution

Our discussion above has not contrasted directly the two solutions to the visual overload problem mentioned in the introduction. We did not directly undertake this analysis, in the interest of reducing the number of condition contrasts to be made, and keeping these contrasts orthogonal

as well as planned. However, were such a contrast to be carried out, in the interest of applied design questions, the evidence would be ambiguous. Both forms of side task delivery appeared to disrupt the safety-critical control task, although through different mechanisms. Auditory “preemption” produced an increase in stick movement, associated with increased error, whereas HUD overlay produced a (apparently intentional) decrease in stick movement, also increasing tracking error. Concerning side task performance, the Auditory delivery appeared to be more effective than the HUD. It is interesting in this light that we have offered a best case opportunity for the auditory task, since the conveyance of digits is a compatible mapping (Wickens, Sandry, & Vidulich, 1983). Fewer auditory benefits might average with more complex auditory information

5.5 Implications for Model of Selective Attention

While the current study is most directly relevant to models of time-sharing, divided attention, and concurrent task performance, some aspects of its results pertain directly to a model of selective attention in large scale space, referred to as the SEEV model (Wickens, Xu, Helleberg, & Marsh, 2001). The components of the acronym are the four factors that are assumed to drive the allocation of attention to channels or sources of information: Saliency, Effort, Expectancy and Value. Neither expectancy nor value were explicitly manipulated in this experiment, but differences across conditions have important implications for the influence of both saliency and effort.

Previous validations of the model have all employed visual channels. However important applications should include the ability to code the saliency of auditory when contrasted with visual information (Wickens & McCarley, 2001). That is, when a visual and auditory event occur simultaneously, to what extent will one or the other tend to capture attention. The current data speak to the generally greater attention-capture (i.e., saliency) properties of auditory events. Their onset was both able to call attention (and initiate the response) in a shorter time, and disrupted the ongoing tracking task to a greater extent (the increase in error a short time following auditory onset). These data offer justification for coding auditory saliency with a higher coefficient than visual saliency in any model of selective attention (Wickens & McCarley, 2001).

The manipulation of spatial separation has implications for both components of saliency and effort. Since our interest in selective attention (given the domain of the SEEV model) is in the initiation of processing (an index of how fast a channel is selected) rather than the quality of the ongoing processing (the domain of divided attention), we focus on the side task RT. The increase in RT across displays V1, V2, V3, V4 (i.e., from 7 to 44 degrees of eccentricity) can be offered three interpretations, which are not mutually exclusive.

1. It took subjects longer to notice the onset of more peripheral stimuli, because of the slower processing of peripheral vision.

2. Subjects adopted a scan strategy to check the periphery for the existence of a stimulus, and were less likely to check at farther regions of eccentricity (hence the mean delay till processing initiation would be longer).

3. Subjects were more likely to bring the tracking task to a temporary state of good control, the more eccentric was the side task onset, because they realized the degrading consequences of more peripheral tracking. Hence they would be inclined to wait longer before initiating the side task, even though they might have noticed it earlier.

The relative influence of the three mechanisms associated with these hypotheses cannot be fully tested, without a measure of eye-scanning, in particular to distinguish 1 from 2. However it may be noted that (1) clearly reflects the influence of salience, whereas (2) is much more related to effort, in that it describes a reluctance to engage in long scans, in particular those with head movements. In this regard, it is informative to recall the inferred role of a corresponding effort mechanism in accounting for the larger increase in RT at the greatest eccentricity (with the longest digits; figure R11), as well as a similar interaction with tracking error (Figure R12). The data do not however enable us to directly associate effort with a particular coefficient value in applications of the SEEV model. They do support however the general form of the model presented in Figure 1, suggesting that the costs of effort are non-linear across separation.

5.6 Models of Time Sharing

The results clearly support models of concurrent task performance, and therefore reject, in this paradigm, the more severe forms of single channel processing, which predict the abandonment of one task, while the other is performed (Liao & Moray, 1993). The strong basis for this support is the fact that even in the most restricted dual task conditions, response velocity is no lower than in the single task condition and therefore far exceeds the 0 level predicted and observed when one stops tracking entirely. Our participants were then endeavoring to track, even as they both perceived and responded to the digit information (see also Tsang, Shaner, & Vidulich, 1995 for corresponding findings).

In more detail, we can examine whether the concurrent performance is best explained by single or multiple resource models. The most direct test of the multiple resource model in the current experiment is the comparison between auditory and visual modality interference, an issue discussed in detail in section 5.1, where support for the modalities of processing dimension was muted. However some indirect evidence for the role of multiple resources on other dimensions is provided by the following interpretation. There was a clear disruption of tracking by the progressively longer voice responses, during the interval while the speech response was ongoing, and this disruption was associated with a significant change in stick behavior. While the side task and tracking demand distinctly different response **codes** (verbal and spatial respectively), they both demand common stage-defined (response) resources, creating a competition which is the apparent source of increased interference with increasing side task load. Furthermore, this dimension along which the two tasks are assumed to compete (stage of processing), appears in the current data to be independent of the codes of processing dimension in the multiple resource model, since the difference between auditory and visual delivery of information (and the resulting code-defined phonetic interference between listening and speaking in the former case), observed to disrupt speaking time (Figure R2) had no effect on performance of the concurrent tracking task while that speaking was ongoing (Figures R3 and R4). Thus the data are consistent with the roles of within-task code-defined interference (Wickens & Sandry, 1982), between-task stage-defined interference, and the relative independence of these two interference mechanisms, all effects that are consistent with a multiple resource approach.

Acknowledgements

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