Proceedings of the 45th Annual Meeting of the Human Factors and Ergonomics Society. Santa Monica, CA: Human Factors & Ergonomics Society. 2001.

WHEN IS LESS MORE? ATTENTION AND WORKLOAD IN AUDITORY, VISUAL, AND REDUNDANT PATIENT-MONITORING CONDITIONS

F. Jacob Seagull,[1] Christopher D. Wickens[1] and Robert G. Loeb[2]
[1]University of Illinois at Urbana-Champaign
[2]University of Arizona

Auditory signals can take the form of "auditory displays" that communicate information redundant to visual displays. These redundant displays may allow offloading some visual workload to the auditory channel. The current study examines the effect of visual, auditory and redundant displays on the performance of a dual-task simulation of patient monitoring. Subjects performed manual compensatory tracking task while monitoring six vital signs of a simulated patient, detecting deviations from normal levels. Monitoring was presented in three display conditions: auditory only, visual only, and redundant. Results indicate that the detection of deviations in visual and redundant conditions were not significantly different, but faster than the auditory display. However, performance in the tracking task was degraded least in the auditory condition, and the redundant display resulted in poorest performance—an example of a negative redundancy-gain. Reasons for this finding are examined through data from eye-movement recordings. This negative redundancy gain is also discussed.

Visual attention is a critical resource for the anesthesiologist (Botney & Gaba, 1995). On the one hand, during procedures, he or she must directly treat and monitor the patient, preparing and administering drugs, being alert as to actions performed by the surgeon that might influence vital parameters, as well as the direct observation of clinical indications from the patient such as skin pallor. On the other hand, it is critically important for the anesthesiologist to monitor a series of parameters, related to respiration and blood circulation, as these are automatically sensed. Unfortunately, in the current workstation layout, these visual parameter displays are not co-located with the patient (McIntyre, 1982), so the anesthesiologist requires extensive eye movements and head movements to re-direct attention from one to the other.

Auditory alerts have been designed to offload this parallel visual monitoring task to some degree, calling the anesthesiologist's attention to out-of-bounds parameter readings, even if visual attention is focused directly on the patient. However the actual benefits of such discrete alarms to attention is problematic for several reasons. Their abruptness may seriously interrupt ongoing tasks (Woods, 1995); they are prone to "alarm false alarms", which may ultimately lead to their being ignored (Sorkin, 1987; Breznitz, 1984); and they are often used for functions far different from the simple alerting for which they were designed (Seagull & Sanderson, 2001).

The solution that we examine in this research to the joint problems of parallel visual monitoring and monitoring unsophisticated alarms is the possibility that an **analog auditory display** of patient parameters can benefit patient monitoring performance (Fitch & Kramer, 1994; Kramer, 1994). This idea is based on Broadbent's (1977) and Woods' (1995) concept of a "preattentive referencing" display. Background signals (such as an auditory stream that corresponds to the patient parameters) can be monitored without the disruption of a discrete onset, typifying an alarm. Yet the divergence of that parameter toward a dangerous level can be sensed, even if full visual attention is focused on the patient's body.

Thus our experiment compares auditory versus visual representation of continuous patient parameters while visual attention is diverted to a simulated patient. We recognize also that continuous auditory monitoring is not a well-practiced task, and so despite its value for attention allocation, it might not always be easily interpretable. Thus a third condition, involving a **redundant** display combining both auditory and visual parameters was included. This condition is predicated on the finding from several investigators that the redundant division of information across modalities can offer "the best of both worlds" (See Wickens and Hollands 2000 for a review). However, it should be noted that sometimes this pattern of redundancy gain is not observed (Helleberg and Wickens, 2001; Tzelgov, 1987).

Our simulation involved participants monitoring six parameters (three respiration, and three circulation) for significant deviations. The parameters were presented visually, auditorally or redundantly, while participants' visual attention was diverted to a task that represented the relatively continuous demands of observing the physical patient. These demands were captured by a visual tracking task, positioned in the middle of the visual parameter display (Figure 1). The allocation of visual attention was monitored by an eye-movement recorder.

METHODS.

Each participant was required to concurrently perform the central manual-tracking task while monitoring the six vital-sign parameters for changes. If the participant detected a change in one of the parameters, he or she would press a button to signify detection. When the button was pressed, the parameter that had deviated would begin to return to its previous (i.e. normal) value.

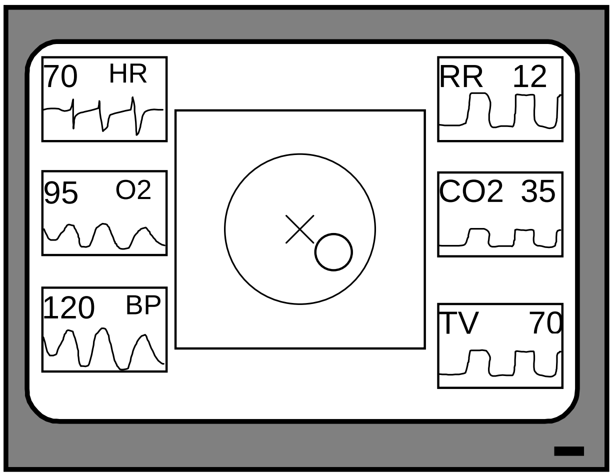

Figure 1: Schematic representation of task display. The center of the screen contains a visual display for a manual-tracking task (compensatory tracking). The perimeter of the screen contains visual displays of the six parameters to be monitored. Heart-related parameters are on the Left, and breath-related parameters on the right.

The visual display (Figure 1) consisted of a manual-tracking task window and six single-parameter windows all displayed within 13 inches horizontally and 9 inches vertically on a video display monitor (subtending 22x15 degrees viewed at 30 inches). The tracking task (first order, compensatory tracking) was positioned in the center of the screen, and measured 9x10 degrees. The remaining single parameter windows measured 4.5x5.6 degrees, and were grouped as three heart-related parameters, displayed on the left side of the screen, and three breath-related parameters displayed on the right. Deviations of the vital signs were represented by changes in the parameter windows' numeric label as well as the analog "trace" lines. Heart parameters included Heart Rate (HR), Oxygen Saturation (O2), and Blood Pressure (BP). Breathing parameters were Respiration Rate (RR), Carbon Dioxide concentration (CO2) and Tidal Volume (TV). Text labels as well as numbers subtended a visual angle of 0.5 degrees.

In the visual-manual compensatory tracking task, the goal was to keep a small circular cursor within a larger target circle, and as close to an "x"- shaped target as possible by manipulating a joystick. The target was always in the center of the screen and did not move, however, the cursor was forced away from the target by a random appearing turbulence function, requiring the participant to use the joystick to move the cursor back to the target. Visually, the tracking task demanded relatively constant foveation for two reasons. First, the contrast between the circular cursor and the background was very low, so that when any of the six peripheral displays of the vital signs were fixated, the cursor could not be discriminated. If a subject focused on the peripheral task for too long, it was even possible to "lose" the cursor briefly upon returning to the central task, as the circular cursor would stray to the edges of the task's display-area and become difficult to detect without a brief visual search of the central task area. Second, the tracking task demanded relatively constant attention for adequate performance. The average bandwidth of the tracking task was 0.18 Hz. Therefore, using the Nyquest frequency as a guideline for how often the manual task needed to be sampled (Moray, 1986), the manual tracking task could be neglected for no more than 2.7 seconds while scanning the peripheral displays. This calculation provides a rough quantitative estimate of the difficulty of the task. Subjectively, subjects reported that they found the task challenging and that they felt that they could only look away from the task very briefly.

The auditory stimuli used were based on the interface developed by Fitch and Kramer (Fitch, 1998; Fitch and Kramer 1994, Loeb & Fitch, 2000). The auditory parameters were presented as two separate streams of audio: the three heart-related parameters were communicated through a heartbeat sound, and the three breath-related parameters were communicated through a breathing sound. Heart rate and respiration rate parameters were communicated by the pace of the heart- and breath-sounds, respectively. Oxygen Saturation and CO2 levels were presented acoustically as the pitch of the heart and breath sounds, respectively. The acoustic timbre-parameter represented either blood pressure (in the heart sound) or volume (in the breath sound).

The particular acoustic parameter values used to signal changes in the auditory modality were established on the basis of a pilot psychophysical experiment of six participants. Based on the difference thresholds calculated from these data, as well as pilot testing of the auditory stimuli, parameters were implemented so that the response time would be roughly equivalent between visual display and auditory display.

Conditions: There were three monitoring conditions (manual-tracking task remained constant).

1. auditory monitoring only
2. visual monitoring only
3. combined (redundant) auditory and visual monitoring

These conditions were tested in a within-subjects design, in which each of the three conditions was presented within two 13-minute blocks of monitoring trials. All subjects carried out all six blocks of trials (order counterbalanced). Following the six blocks, subjects also carried out a post-test session for single-task performance levels for visual-only and auditory-only monitoring, with no manual task.

Eye movements were monitored with an ASL-500 series eye-tracking system with remote optics (Applied Science Laboratories).

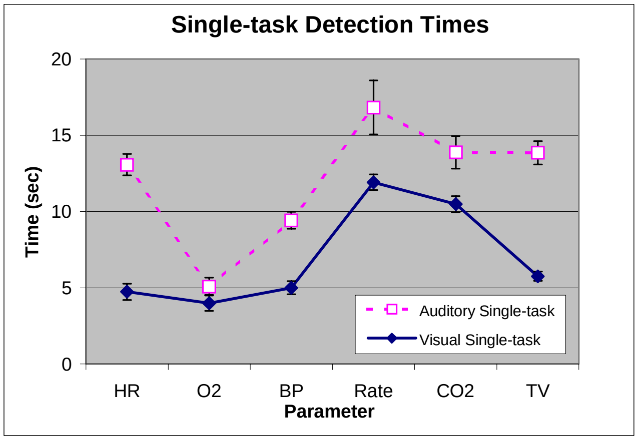

Figure 2: Detection times for single-task conditions in post-test trials for Visual-only and Auditory-only display conditions.

RESULTS

Figure 2 shows the single task (i.e., without tracking) parameter deviation detection time, as a function of parameter type and modality (auditory – visual). The results reveal a main effect of display modality ($F = 86.8$ $p<.01$), when visual attention was not diverted to the tracking task, indicating approximately 5 second slower detection with the auditory than the visual display. We had not anticipated this, given our pilot experiment designed to psychophysically equate the discriminability.

Figure 3 presents the dual task patient monitoring data, now including the redundancy condition (which was not run in single task conditions). The significant effect of modality ($F = 26.6$) reveals again a cost for auditory monitoring, relative to both the visual and the redundant conditions, which were equivalent in their performance. However, it is apparent that the auditory cost is somewhat reduced, relative to its single task values, and indeed appears to be eliminated for two of the parameters (O2 and CO2). This reduction was confirmed by a third analysis performed on the dual task **decrement** scores (dual – single task RT), carried out on only the two single-modality conditions. This analysis revealed that the auditory decrements were significantly smaller than the visual decrements for all parameters except one.

The interference between the two tasks was also assessed by examining the dual-task tracking-error across the three dual-task conditions, as shown in Figure 4. (These were not divided by parameter type as in Figures 2 and 3, because participants were assumed to be monitoring all parameters more or less concurrently). Analysis of the tracking decrement revealed a marginally significant effect of modality ($F = 3.0$, $p<.069$), favoring the auditory modality, and showing poorest performance when parameters were monitored with the redundant modalities.

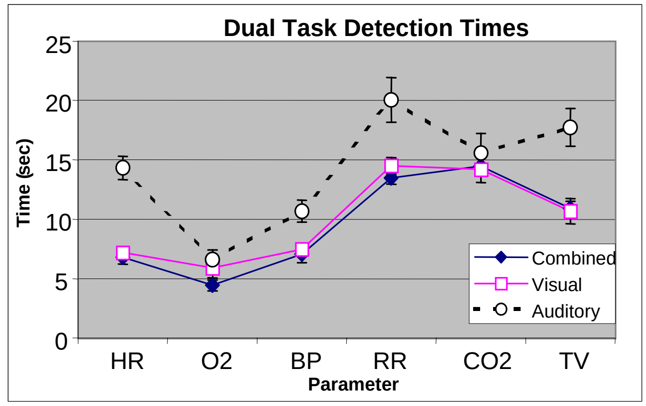

Figure 3: Target detection times during dual-task performance for the three display conditions and the six parameters.

We attempted to diagnose the source of this somewhat unexpected result (a redundancy "loss" in tracking performance) by examining the visual scanning measures, shown in figure 5. This analysis revealed several characteristics: (1) with visual displays, participants paid more attention to the patient (tracking task) than to parameter monitoring. (2) Not surprisingly, when the display was only auditory, little attention was allocated to the visual display, yielding a large gain in attention to the tracking task (whose performance benefited as a result, as shown in Figure 4). (3) There was no difference in attention allocation between the redundant and the visual-only condition. On the one hand, this equivalence can account for the failure to observe a redundancy gain in either tracking or patient monitoring; participants may simply have disregarded the auditory display when it was coupled with the visual. But the equivalence cannot account for the actual loss. Subsequent interviews with participants revealed that some had difficulty resolving or "harmonizing" the two different modality signals, a distraction that probably had an added cost to their tracking performance.

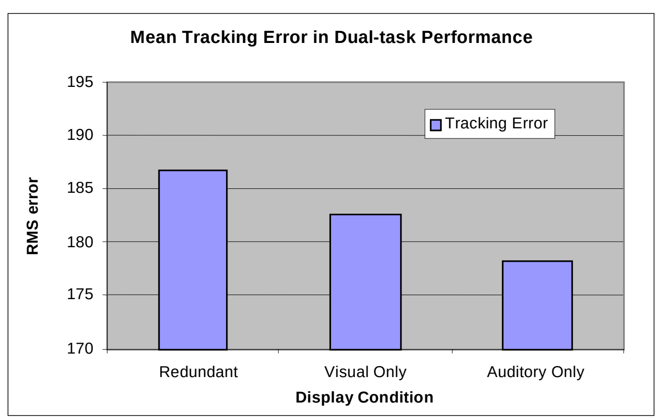

Figure 4: Tracking Error in Dual-task performance for the three display conditions.

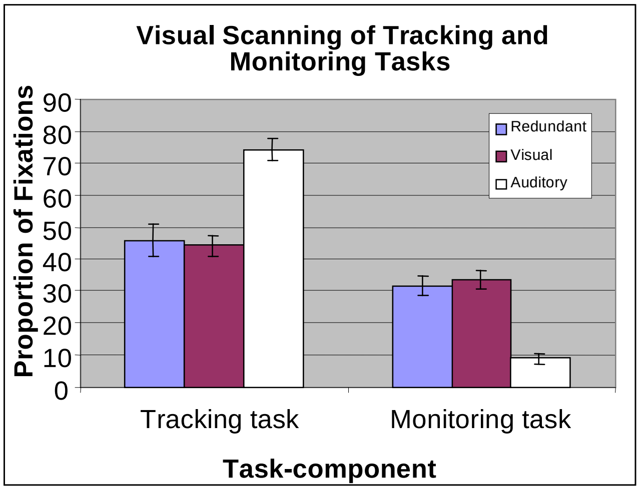

Figure 5: Visual Scanning of central and Peripheral displays during dual-task performance, for tracking task window and (combined) vital-sign monitoring windows for the three different display conditions.

We also performed additional analyses on the visual scanning data across the six parameter windows of the display for the two display-conditions involving visual display components: the visual-only and the combined displays (Figure 6). The results of these analyses have been used to model the data in terms of how attention is driven by the factors of channel bandwidth and scanning effort (Moray, 1986; Wickens Xu Helleberg and Marsh, 2001).

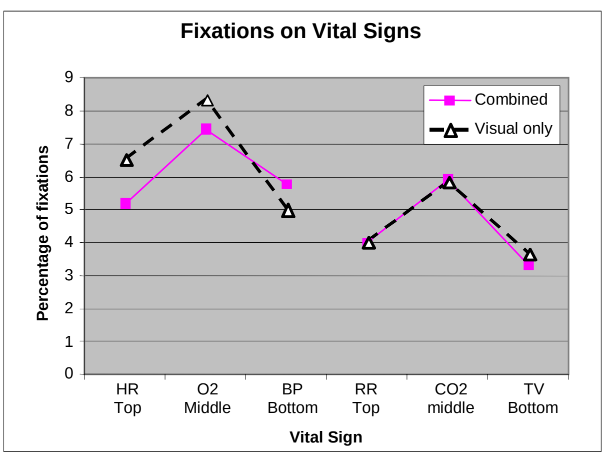

Figure 6: The proportion of fixations for Combined display and Visual-only display, for the six vital-sign parameter windows, grouped by side of display into Heart (HR, O2, BP) on left and Breath (RR, CO2, and TV) on right, arranged in order from top to bottom.

Three characteristics should be pointed out about Figure 6. First, the group of three heart-related parameters, shown on the left side of the graph, has a higher bandwidth of change than the breath-related parameters shown on the right. Consequently, the group of heart-related parameters shows significantly a higher proportion of fixations ($F(1,8)=7.268$ $p<.027$). This supports previous findings of bandwidth's influence on visual sampling (e.g. Carbonell, et al., 1966; Moray, 1986; Senders, 1980).

Second, the information-access cost (i.e. effort of visually scanning) influenced scanning behavior. The middle parameter windows (O2 and CO2) were sampled significantly more frequently than the top and bottom windows ($F(2,16)=4.89$; $p<.022$). The increased sampling of the middle window could be due to the ease of horizontal saccades (Alpern, 1969) from the central task to the middle windows in comparison to vertical or diagonal saccades to the top and bottom windows. The middle windows were also closest to the central tracking-task display (see Figure 1).

Lastly, it should be noted that the combined display appears to have significantly reduced scanning to two of the three heart-related parameters ($F(2,16)$ 4.52; $p<.038$). The reduction may have been the result of participants' ability to use the auditory component of the combined display to supplant visual scanning.

DISCUSSION.

It is apparent that continuous auditory display of parameters can avail increased visual attention toward a "primary task" (here the tracking task, in the operating room, the physical view of the patient). Although those auditory parameters appear to be more difficult to monitor than their visual counterparts, this added perceptual/cognitive difficulty did not appear to be adequate to neutralize the benefit offered by the fully available visual channel. The tradeoff between poorer parameter-monitoring performance versus better patient-monitoring performance, when continuous auditory signals are used could seemingly be addressed by availing greater practice and training for participants to interpret the auditory signals. Our participants here were not trained medical personnel, for whom the association and semantic meaning of the sounds might have been greater, reducing their difficulty of processing.

The failure to find any advantage in target detection for redundant display (and indeed some cost in manual tracking), while unexpected here, was not without precedence. Helleberg and Wickens (2001), examining communications displays for the cockpit also found that a redundant display of text and speech failed to provide "the best of both worlds" (although they found that its performance was in-between the two single modality conditions). Tzelgov (Tzelgov, et al., 1987) also found better performance in a single-modality auditory display than a combined (redundant) visual-auditory display in a search task. In the current data we believe that the interpretation of this result may again lie in training. Better training with auditory monitoring should raise its level of performance somewhat, and better training in attention allocation (Gopher, 1993) should provide participants with a better understanding of when, in the redundant condition, it is most appropriate to leave the tracking display for a cross check with the visual display.

ACKNOWLEDGEMENT

The efforts reported here were partially funded by a grant from the National Patient Safety foundation at the American Medical Association.

REFERENCES

Alpern, M. (1969). Types of Movement. In H. Davison (Ed.), *The Eye. 3* (2nd ed.). New York: Academic Press.

Botney, R. & Gaba, D.M. (1995). Human Factors Issues in Monitoring. In C. D. Blitt, and R.L. Hines (Eds.) *Monitoring in Anesthesia and Critical Care Medicine* (3rd Ed.). pp. 23-54. New York: Churchill Livingstone.

Breznitz, S. 1984. Cry Wolf: the Psychology of False Alarms. Lawrence Erlbaum Associates, Hillsdale, New Jersey.

Broadbent, D. E. (1977). The hidden preattentive processes. *American Psychologist. 32*(2), 109-118.

Carbonell, J. R. (1966). A queueing model of many-instrument visual sampling. *IEEE Transactions on Human Factors in Electronics, HFE-7* (4), 157-164.

Fitch WTS (1998) Sonification system using synthesized realistic body sounds modified by other medically-important variables for physiologic monitoring. U. S. Patent Number 5730140

Fitch, W. T. and Kramer, G. (1994): Sonifying the Body Electric: Superiority of an Auditory over a Visual Display in a Complex, Multi-Variate System. In: "Auditory Display: Sonification, Audification, and Auditory Interfaces" (Ed. G. Kramer). Santa Fe Institute, Studies in the Sciences of Complexity, Vol 18. Reading, MA: Addison-Wesley.

Gopher, D. (1993). The skill of attention control: Acquisition and execution of attention strategies. In D. E. Meyer & S. Kornblum (Eds.), Attention and Performance XIV (pp. 299-322). Cambridge, MA: MIT Press.

Helleberg, J. and Wickens, CD (2001) Effects of data link modality on pilot attention and communications effectiveness. In R. Jensen (Ed) Proceedings of 11th International Symposium on Aviation Psychology. Columbus Ohio: Ohio State Univ.

Kramer, G. (Ed.) (1994). Auditory Display: Sonificanton, Audification, and Auditory Interfaces. Reading, MA: Addison Wesley.

Loeb R. G., & Fitch W. T. (2000). Laboratory evaluation of an auditory display designed to enhance intra-operative monitoring. *Journal of Clinical Monitoring and Computing, 16*, 63-64.

McIntyre, J. W. R. (1982). Man-machine interface: the position of the anesthetic Machine in the operating room. *Canadian Anesthesia Society Journal, 29*, 74-78.

Seagull, F. J., & Sanderson, P. M. (2001). Anesthesia alarms in context: An observational study. *Human Factors,43*(1), 66-78.

Sorkin, R. (1987). Design of Auditory and Tactile Displays. In G. Salvendy (Ed.) Handbook of Human Factors.

Tzelgov, J., Srebro, R., Henik, A. & Kushelevsky, A. (1987). Radiation search and detection by ear and by eye. Human Factors, 29(1), 87-95.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd Ed.). Upper Saddle River, NJ: Prentice Hall.

Wickens, Xu, X., Helleberg, J and Marsh, R (2001)Pilot visual workload in free flight: a visual scanning study. In R, Jensen (Ed) Proceedings 11th International Symposium on Aviation Psychology: Columbus Ohio: Ohio State.

Woods, D. D. (1995). The alarm problem and directed attention in dynamic fault management. *Ergonomics*, 38(11), 2371-2394.