Auditory Warning Signals in Critical Care Settings

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Acknowledgement

The project team thanks many people from University of Maryland R Adams Cowley Shock Trauma Center, Uniformed Services University of Health Sciences, and Army Research Laboratory (Aberdeen) for their generous support for this project. In particular, we would like to express our gratitude to Richard Dutton, MD, Mahmood Jaberi, MD, Don Steinke, Peter Hu, MS, CNE, Clifford Boehm, MD, Dale Downy, Richard Kyle, Debbie Patton, and Pam Burton. Their support made possible the accomplishment of this project. The project team would also like to thank the guidance of the National Patient Safety Foundation.

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1. Overall summary of the project

a) Original hypothesis and objectives

The goal of this project was two-fold: to demonstrate the value of cognitive engineering in understanding safety enhancing technology, and to understand the roles of auditory alarms in patient monitoring. The project had three specific aims: (1) to determine patterns of information usage during real and simulated anesthesia, (2) to develop a general framework which depicts the role of and need for (i) auditory warning signals for alerting and (ii) auditory "updating" signals in patient monitoring, and (3) to produce a set of tentative design principles for such auditory display of monitoring signals in critical care.

b) Methods used

The key and innovative method developed and used in this project was an ambulatory eye-tracking device that captured eye-gaze data during real and simulated patient care. Two complimentary studies were conducted on the informational value and user responses to auditory warning signals in critical care settings: (1) a prospective, comprehensive (video-based with ambulatory eye-tracking devices) data collection in real patient care (anesthesia induction and airway management) and (2) a set of experiments in a high-fidelity environment, also with the use of eye-tracking devices. Figure 1 illustrates the data collected in the real patient care environment (a surgical operating room).

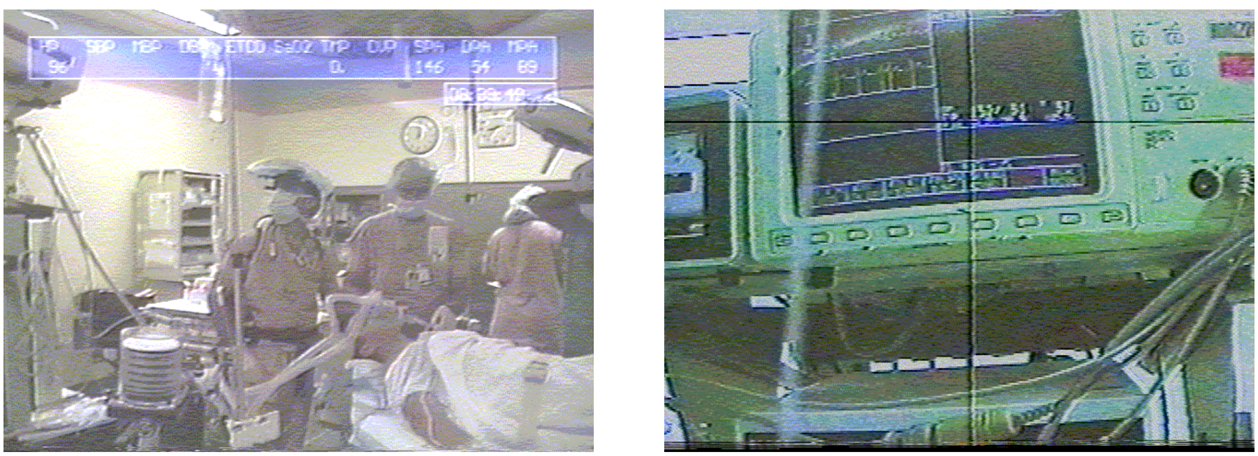


Figure 1. Examples of the data collected. ***Left****: Lateral camera view video recordings, showing the anesthesia care provider (left) wearing the ambulatory eye-tracker. The headset was covered by a surgical cap. The video image captured shows the subject was looking at a patient monitor while ventilating the patient through a facemask.* ***Right****: Eye-gaze data, represented by video recordings from a head-mounted camera, overlaid with eye-gaze position (black cross hairs). Shown here was a video image captured when the subject was looking at a patient monitor.*

The eye-tracking device used was from Applied Science Laboratory (ASL). The device was packaged in a backpack and collected eye-gaze position data through a head-mounted camera and an infrared eye-position measuring mechanism. Video images from the head-mounted camera were recorded, which provided a general field of view from the perspective of the device wearer. The eye-gaze positions were in the form of cross-hairs overlaid onto the video images of visual fields.

In the real and the simulated settings of the two studies, between the cases, the criteria-settings of the alarm-systems were manipulated to either default settings ("Control condition"), or to a more "strict" settings, meaning alarms sound when smaller deviations are detected ("Strict condition"). These manipulations were carried out for four main vital signs: heart rate, blood pressure, oxygen saturation, and exhaled Carbon Dioxide level (EtCO2) (Table 1).

Vital Sign	Control Condition Alarm Settings	Strict Condition Alarm Settings
Heart Rate	Baseline ± 30%	Baseline ± 10%
Blood Pressure	Baseline ± 30%	Baseline ± 10%
Oxygen Saturation	Alarm Below 90%	Alarm below 96%
CO2 Exhaled (EtCO2)	Alarm <24, >55	Alarm <30, >45

Table 1: Equipment Settings for the strict and control conditions in real and simulated cases.

For the study in the real environment, the anesthesia induction and airway management (intubation) of elective surgery cases was selected for data collection based on logistical considerations. For the study in the simulated environment, two scenarios were designed surrounding the similar task: anesthesia induction and airway management. Simulated patient care was conducted with a full-mission, hands-on, high-fidelity patient simulation environment in Uniformed Services University of Health Sciences (Figure 2).

Figure 2. Project team was discussing scenario scripts for simulated airway management, in which alarms were manipulated to examine care providers' information gathering patterns. From left to right: Darin Via, MD, Jacob Seagull, PhD, Yan Xiao, PhD, and Richard Kyle. The simulation took place in the patient simulation lab at Uniformed Services University of Health Sciences, Bethesda, Maryland.

The resulting videotapes were manually coded to extract information on the activities and eye fixations of the care provider. Eye fixations and activities were coded into three categories: (1) looking at the patient or other care providers, (2) looking at monitoring equipment, and (3), manipulating the monitoring equipment (i.e. adjusting settings of any patient monitoring or support device).

c) Results
The eye-gaze data from 16 real cases in operating rooms and 30 simulated cases. Detailed results were reported in papers and abstracted listed elsewhere. Here are the outline of some of the research results:

i). It was feasible to deploy ambulatory eye-trackers in clinical environment. The ambulatory eye-tracking device was successfully used during the high-workload period of anesthesia induction and airway management. Differences in monitoring frequency by the anesthesia care providers were quantified for different stages of anesthesia care.

ii). Presence of auditory alarms correlated with the length of airway management. When there were more alarms as the result of experimental manipulation, it took longer (54 s vs. 34 s) to accomplish laryngoscopy and intubation. The results support the hypothesis of the negative impact of false alarms. Combined with previous studies on auditory alarms, the results suggest that current auditory alarms could adversely affect care provision. Design of alarming devices needs to consider the negative impact of auditory alarms.

iii). Care providers looked at different things in real operating rooms compared to during simulation. Using an eye-tracker, we compared anesthesia care providers' visual scanning patterns during induction of anesthesia in real elective surgery with the patterns in simulated airway management. In simulation, care providers spent less time looking at the patient, and checked the monitoring equipment more frequently. The simulated patient seemed to be less informative and thus clinicians information from monitoring devices. This suggested potential limitations in evaluating care providers' monitoring behavior in a simulated environment.

iv). Care providers varied their monitoring behaviors during different phases of their tasks. We attempted to compare how frequently the anesthesiologist looked at the vital signs monitors during the induction of anesthesia. Five time periods were selected for comparison: preparation for induction, induction, pre-oxygenation, intubation, and one minute post-intubation. The results did show statistically different sampling rates in the five selected periods. There was a large increase of sampling rate immediately after intubation, whereas during intubation the sampling rate was zero.

2. Impact to Patient Safety

Is the health care environment in hospitals and clinics friendly to the health care providers? Are devices designed with considerations of how they should improve patient safety? If answers to these two questions are negative, how should we make the health care environment more user friendly? This project examined these questions using auditory alarms as a case in point, using methodologies of cognitive engineering.

Designers have long adopted the practice of attaching alarms of various types to displays and devices. In many senses, such practice is well-intentioned: it aims at well-known limitations in human performance, such as attention spans and difficulties in tracking many parameters: Control room operators can be warned of leaking valves; anesthesiologists can be warned of disconnected circuits; pilots can be warned of low fuel levels; train operators can be warned of over-heated engines. On the flip side, however, in almost every work setting in which alarms are deployed, there are reports of inappropriate alarms.

During patient care an anesthesiologist gathers information from a variety of sources to ensure patient's safety. Much of the information is through the eyes. Knowing where an anesthesiologist looks could thus provide a basis for estimating what information is needed and determining how best present the needed information to the anesthesiologist. Measuring eye-gazes while an anesthesiologist cares for a patient is a direct, objective way of collecting data of anesthesiologist's visual scanning patterns. However, technical difficulties abound for deploying such methods. We tested a commercial ambulatory eye-tracking device during the induction of anesthesia for elective surgery. The collected eye-gaze data were used to analyze how frequently anesthesiologists looked at various patient monitors.

The study established the feasibility of using an ambulatory eye-tracking device in the operating rooms. Whereas the findings of the analysis were not unexpected, they provided an objective basis of quantifying information gathering patterns of the anesthesiologist. During induction of anesthesia, the anesthesiologist has a high workload. Effective means are needed to provide patient status information to the anesthesiologist. Currently the vital signs monitors are scattered around the patient, making it difficult to gather information. For example, during intubation during which the sampling rate was zero in this study, well-positioned patient monitors could make it possible for the anesthesiologist to detect problems early.

There are potentially many uses of eye-gaze data. For example, further analysis of the recorded data from the current study will establish the feasibility of discerning which parameter the anesthesiologist looks at and when. Ambulatory eye-tracking devices could also be used in comparing different designs of patient monitors, evaluating different monitoring strategies that may be used by the anesthesiologist, and best allocation of patient monitors. Interestingly, data from eye-tracking devices may be analyzed to guide the design of innovative auditory "displays": presenting patient status information through sound. Eye-gaze data could then demonstrate whether or not the anesthesiologist spends more time looking at the patient when auditory displays are used.

Patient safety can be improved substantially if cognitive engineering is used routinely in the design of critical safety devices. Groundbreaking advances can be made in information provision for patient monitoring and for safeguarding the patient.

This project represents a new approach to understanding the information value of auditory alarms.   Problems with alarms have been a high profile topic for a variety of reasons. As a prominent example of safety-enhancing technology deployment, various auditory alarm mechanisms have been introduced to improve patient safety, yet study after study has shown that alarms in clinical environment are confusing, obtrusive, and uninformative. Instead of being a mechanism safeguarding the patient, alarms often increase workload, make communications difficult, and produce a hostile work environment.

3. Future plans for implementation and dissemination

A web site is under development to make available knowledge and information acquired during the project (http://hfrp.umm.edu/alarms). The website will contain materials related to the alarm problems in general in patient monitoring, suggestions to clinicians and purchasers, publications and presentations related to the project, and resources (e.g. bibliographies) collected during our research on alarms. Two journal paper manuscripts are under preparation to publish the research efforts. We also are actively involved in the University of Maryland Medical Center's efforts in patient safety, which include identification of patient monitor related problems.

4. Future plans of this project

The eye-tracking data collected during this project is an important source for understanding monitoring behaviors of clinicians. We plan to further analyze the data to model monitoring behaviors. We also plan to extend the experiments conducted in controlled laboratory settings to understand how auditory "displays" can improve patient safety.

5. Other sponsorship for research

Since the award of the NPSF grant, our research group has received a grant from Agency for Healthcare Research and Quality for studying chest-tube placement with the use of video recording, two grants from National Science Foundation for studying coordination in trauma care, and a grant from Army Research Institute for studying team performance and leadership during trauma care. The NPSF funding has been instrumental for obtaining these multi-year grants that support research examines various aspects of patient safety. Below are the details of the grants received since the award of the NPSF grant:

Funding Agency: National Science Foundation
Title: Coordination Processes and Awareness Support
Investigators: Yan Xiao (PI), Colin Mackenzie, Samer Faraj, Mary Etta Mills, Anthony Norcio
Total Costs: $199,998 (10/1/99 – 9/30/01)

Abstract: Dynamic work environments require team members to maintain an awareness of resources, incoming workload, and activities and knowledge of other people for the purpose of coordinating plans and activities, often across time and location. This proposal systematically investigates the coordination processes used by distributed expertise teams operating in high velocity work environments. We will explore how existing coordinative artifacts are used to support awareness by team members of each others' status, current and forthcoming workload, and understanding of the task. We will also introduce and study the impact of new digital coordination technologies and evaluate how the properties of computer-enhanced coordinative artifacts affect awareness support. Ethnographic studies, surveys and interviews will be conducted in a real, highly dynamic, multi-tasking, multi-disciplinary work environment. The proposed three-year effort will establish a theoretic-empirical basis for augmenting coordination processes in teams through computer technology. The two main objectives of the proposal are: (1) to develop a framework for modeling coordination processes by team members in highly dynamic, multi-tasking environments and (2) with the guidance of the framework, to explore a category of awareness support techniques based on shared visual displays.

Funding Agency: National Science Foundation
Title: Expertise Coordination and Information Technology
Investigators: Yan Xiao (PI), Colin Mackenzie, John Welton, Samer Faraj
Total Costs: $ 499,916 (10/1/00 – 9/30/03)
Abstract: High velocity work environments such as medical trauma centers depend on robust and efficient coordination by team members to bring together appropriate knowledge and skills, or expertise. This project investigates the existing and potential role of information technology (IT) in expertise coordination in a type of high velocity, high outcome work environments: level-I trauma centers in this country. A combination of qualitative and quantitative methods are used to collect observational and survey data in a range of trauma centers regarding: the expertise needs of trauma medical teams, the points of expertise needs, the modes of acquiring needed expertise, the sources of information related to work and expertise coordination, uses of IT for the coordination of needed expertise, as well as broader organizational variables. The project will contribute to the development of guiding principles in the design of next generation IT for high velocity work environments in the areas of user interfaces, contents, coordination mode, and evaluation of the impact of IT on coordination. It will contribute to the understanding of expertise coordination and how IT affects its processes. Finally, the project will enhance an existing multi-disciplinary research program on information and coordination related issues in emergency trauma care.

Funding Agency: Department of Defense
Title: Distant Leadership under Stress
Investigators: Yan Xiao (PI), Colin Mackenzie, Thomas Scalea, Victor Giustina, Peter Hu
Total Costs: $146,866 (8/1/99 – 7/13/02)
Abstract: The project is to investigate relationships between leadership and team performance when leaders are at a distance. Leadership in team performance can hardly be overstated in many situations, understanding how leadership is related to team performance is important to military as well as civilian organizations. With widespread use of electronic communication technologies, it becomes essential to establish a theoretical and empirical basis for predicting

how new communication technologies impact on leadership and team performance. To better understand distant leadership under stress, we propose a three-year project with two intertwining lines of efforts: (1) to develop a conceptual model of the interaction between task structure, stress levels, communication modality, and leadership effectiveness; (2) to conduct an empirical study of distant leadership using a real, dynamic, and stressful work environment as a laboratory. specific aims: (a) developing a matrix of leadership functions and situations in which leadership functions are needed; (b) developing a model of nominal leadership processes through which a leader applies control over and influence on team activities, either co-located or at a distance; (c) developing process measures of leadership in a team environment; and (d) conducting a series prospective studies in a real, event-driven, stressful environment to evaluate the impact of various communication modalities on leadership, using the measures developed.

Funding Agency: National Institutes of Health
Title: Brief Risky High Benefit Procedures: Best Practice Models
Investigators: Colin Mackenzie (PI), Yan Xiao, Grant Bochicchio, William Chiu, Aurelio Rodriguez, Lynn Gerber-Smith, Peter Hu, Susan Bogner
Total Costs: $545,914 (1/1/01 – 12/31/03)
Abstract: To demonstrate the value of a video-based procedural analysis and to develop a research framework for studying the effects of team and environmental factors on performance. Such detailed video, task, and ergonomic analyses may be useful in many emergency procedures as a means of categorizing and developing best clinical practice models.

6. Publications and Presentations

The research supported in part or in whole by the NPSF grant has produced a number of publications, in which the support from NPSF was acknowledged. One abstract presented at the 1998 annual meeting of American Society of Anesthesiologists (ASA) was selected as one of the 15 abstracts (out of more than 1400) to be featured as press releases. The abstract presented at a meeting sponsored by Society of Technology in Anesthesia was awarded as the best research abstract.

In addition, a PhD dissertation was partially funded by the project. Dr. Seagull, who was a co-principal investigator, conducted a series of studies on auditory alarms and displays in his dissertation research.

1. Seagull, F.J., Xiao, Y., Mackenzie, C.F., Jaberi, M., & Dutton, R. Monitoring behavior: a pilot study using an ambulatory eye-tracker in surgical operating rooms. Proceedings of Human Factors and Ergonomics 43rd Annual Meeting, pp. 850-854, 1999.
2. Xiao, Y., & Seagull, F.J. An analysis of problems with auditory alarms: defining the roles of alarms in process monitoring tasks. Proceedings of Human Factors and Ergonomics 43rd Annual Meeting, pp. 256-260, 1999.

3. Seagull, F.J., Xiao, Y., Mackenzie, C.F., & Wickens, C.D. Auditory alarms: From alerting to informing. Proceedings of IEA 2000/HFES 2000 Congress, Vol 1, pp. 223-226, 2000.
4. Xiao, Y., & Seagull, F.J. Auditory Warning Signals: New Concepts and Approaches. Proceedings of IEA 2000/HFES 2000 Congress, Vol 1, p. 210, 2000.
5. Xiao, Y. Mackenzie, C.F., Seagull, F.J., & Jaberi, M. Managing the Monitors: An Analysis of Alarm Silencing Activities During An Anesthetic Procedure. Proceedings of IEA 2000/HFES 2000 Congress, Vol. 4, pp. 250-253, 2000.
6. Seagull, F.J., & Xiao, Y. Patients Monitoring Technology: Friend or Foe? Proceedings of IEA 2000/HFES 2000 Congress, Vol 4, p. 249, 2000.
7. Seagull, F.J., Xiao, Y., Dutton, R., Downey, D., & Jaberi, M. Diagnosis In Real and Simulated Environments: Do We Look At Different Things. Anesthesiology, 93(34): A-572, Sept. 2000
8. Xiao, Y., Via, D., Kyle, R., Mackenzie, C.F., & Burton, P. Stress with Simulated Trauma Management Measured Salivary Amylase. Anesthesiology, 93(34): A-1226, Sept. 2000
9. Xiao, Y., Seagull, F.J., Jaberi, M., & Downey, D. Experimental use of an ambulatory eye-tracking device in operating rooms (OR). Anesthesiology, 89(A3):A1137, 1999.
10. Darin K. Via, Richard Kyle, Yan Xiao, Jacob Seagull, Colin MacKenzie, Eye Tracking System Improves Evaluation of Performance during Simulated Anesthesia Events, 2001 Society for Technology in Anesthesia International Meeting on Medical Simulation.
11. Seagull, F.J., Wickens, C.D. and Loeb, R.G. (In press). Attention and workload in auditory, visual, and redundant patient-monitoring conditions. Proceedings of the Human Factors and Ergonomics Society annual meeting, 2001.
12. Seagull, F.J., Xiao, Y. (In press). Using eye-tracking video data to augment knowledge elicitation in cognitive task analysis. Proceedings of the Human Factors and Ergonomics Society annual meeting, 2001

7. Career and Research Direction

The research supported by NPSF grant has significant impact on the career development in both Principal Investigators: Yan Xiao and Jacob Seagull. Over the course of the NPSF sponsored project, Yan Xiao has further developed the human factor research program and became the program director. He was recently promoted to the rank of Associate Professor with tenure in part due to the accomplishment in research on patient safety and alarms. Jacob Seagull was accepted as a post-doctoral fellow in the Human Factors & Technology Research, continuing with his research in patient safety. His accomplishment in alarm research supported by NPSF was the primary factor in his appointment.

The grant from NPSF has brought prestige in general to the research program in human factors, both internally in the University of Maryland School of Medicine and its affiliated hospitals and externally to colleagues around the country. The research activities associated with the NPSF project have also provided more visibility of human factors research to clinicians and enhanced the rapport of clinicians in other patient safety related research. Additionally, the NPSF project provided opportunities for collaborative research with Uniformed Services University of Health Sciences.

We plan to continue the research in monitoring behavior of clinicians in general and hope to capitalize on the expertise and knowledge gained during the NPSF project.

8. Financial report

The original budget of $50,000 (direct and indirect cost) was for one-year. We extended the project to two years to allow adequate time for data analysis. The fund was expended according to the original budget plan with several minor deviations. In the request for one-year no-cost extension, we asked if line-item revision was needed (although no responses were received for the question; see a correspondence dated November 29, 1999, to Dr. Cooper).

	Budget Requested	Actual expenditure
A. Personnel	$ 40,800	$ 33,540
B. Consultants	$ -	$ -
C. Equipment	$ -	$ 6,038
D. Supplies	$ 1,150	$ 2,125
E. Patient/subject costs	$ -	$ -
F. Travel	$ 1,500	$ 1,747
G. Other costs	$ -	$ -
H. Total direct cost	$ 43,450	$ 43,450
I. Indirect costs	$ 6,518	$ 6,518
J. Total funds requested	$ 49,968	$ 49,968

9. Feedback About NPSF Research Program

The NPSF research program has provided an effective framework for reporting while at the same time giving us the latitude in planning and conducting research. We believe the structure of monitoring and administering NPSF research projects is close to ideal. As the recipient of the first NPSF grants, this is a remarkable achievement on the part of NPSF's research committee and has demonstrated NPSF's foresight.

10. Suggestions to NPSF in implementation and dissemination

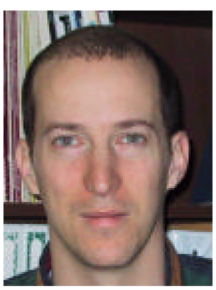
Given the importance of research in patient safety, NPSF has been instrumental in disseminating related information to the public and the research community. If anything, NPSF may consider providing awardees more suggestions and guidance in the areas of how to communicate research results to the lay public and clinicians.

11. Plan for future collaboration with NPSF

We are strongly interested in future involvement in NPSF sponsored or initiated activities. The involvement can be in the form of participating in review of research proposals and publications, in organizing meetings and events, and in providing supporting materials furthering NPSF's mission. We are glad to hear about the idea of an NPSF Research Grantee alumnus program. Such program can bring continuous affiliation with the nation's premier patient safety organization and encourage future communication and collaboration with other awardees. It should also make us more aware of the on-going activities of NPSF.

12. Biography

Yan Xiao is associate professor (tenured) of anesthesiology and information systems and a special member of faculty in School of Business, University of Maryland, College Park. Yan Xiao has a PhD in Human Factors from University of Toronto (1994). He also has MASc in Systems Engineering (1985) and BASc in Mechanical Engineering (1982). Currently he directs Human Factors and Technology Research.



Frank Jacob Seagull is post-doctoral fellow in Human Factors & Technology Research at University of Maryland School of Medicine. He has a PhD in Human Perception and Performance from University of Illinois at Urbana-Champaign (2001). He has researched human factors (HF) topics including human-computer interaction (HCI), advanced displays for aviation, and human performance in the medical domain. Primary interest presently is applying the lessons learned in HCI, Aviation and other traditional HF domains to the medical setting to improve patient safety and medical effectiveness.

Colin F. Mackenzie (left) is Professor of Anesthesiology and Director of National Study Center for Trauma and Emergency Medical Services at University of Maryland, Baltimore. Darin Via (right) is Assistant Professor of Anesthesiology at Uniformed Services University of Health Sciences, Bethesda, Maryland. Shown in the picture were Drs. Mackenzie and Via in designing simulation scenarios.

Richard R. Kyle, Jr. is Director of the Patient Simulation Laboratory (http://www.usuhs.mil/psl), Uniformed Services University of Health Sciences, Bethesda, Maryland.