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Exploring auditory displays to support anaesthesia monitoring: Six questions from a research program

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Abstract

Anaesthetists work in a visually and acoustically complex environment from which they must extract information about the well-being of an anaesthetized patient. Many studies have shown that auditory alarms, designed to recall attention to parameters with abnormal readings, have serious limitations. To circumvent this we have been investigating whether continuous auditory information displays, or sonifications, might be more effective. Specifically, we have developed a sonification of respiration (breathing) intended to complement the heart monitor sonification commonly used and have tested its effectiveness in different ways. This report outlines our most important findings to date.

Introduction

The safety of patients undergoing any kind of medical intervention is an increasing concern in society. For many years, the anaesthesia community has played a leading role in advancing patient safety, in collaboration with human factors psychologists and cognitive engineers (Bogner, 1994). In what follows, I outline a set of questions that we have asked over the last four years within the Cognitive Engineering Research Group—originally at Swinburne University of Technology and more recently at The University of Queensland—about the effectiveness of auditory displays for the operating theatre.

Six questions in a research program

The research program outlined here started with operating room observations I conducted in the USA with PhD student Jake Seagull in the mid-1990s. It became clear that alarms were not giving anaesthetists the right information in the right format at the right time (Seagull & Sanderson, 2001). It was also clear that anaesthetists' activities were subtly attuned to incidental acoustic information in the operative environment, such as the noise of the blood-pressure cuff being inflated reminding the anaesthetist to catch up on charting.

Around this time cognitive engineers were increasingly noting the benefits of background auditory information and calling for auditory displays to be more informative than alerting (Woods, 1995). Some years earlier, Fitch and Kramer (1994) had experimented with a complex sonification for physiological monitoring and had found that monitoring was better in the sonification condition than with a visual display. Although there are shortcomings to Fitch and Kramer's research that are discussed elsewhere (Watson & Sanderson, 2001),

their research still represents a seminal step in this area. A small community now continues the work initiated by Fitch and Kramer (1994). Reports can be found in Seagull, Wickens, and Loeb (2001), Loeb and Fitch (2002), Sanderson, Crawford, Savill, Watson, and Russell (in press), Watson and Sanderson (2001), and Watson, Sanderson, Woodall, and Russell (2003).

The respiratory sonification that is the subject of the studies reported here was co-developed by Marcus Watson and me (Watson & Sanderson, 2001). Because each of the following research questions has been posed in the context of a research thesis topic, I note the research student's name and degree.

1. Does our respiratory sonification work?

For his PhD thesis, Marcus Watson compared several ways of sonifying the respiration rate (RR), tidal volume (Vt, or amount of gas going in and out of the lungs, and end-tidal carbon dioxide (ETCO2, or waste gas coming out in each breath) of a computer-simulated patient undergoing anaesthesia (see Watson & Sanderson, 2001). We had developed a basic sonification that uses the length, sound intensity, and pitch of two successively-played tones to represent the respiration rate, tidal volume, and end-tidal carbon dioxide through its inhalation and exhalation.

Our initial study was to test whether a respiratory sonification would convey information about the patient's respiratory status as effectively as the pulse oximetry system (the beeping heart monitor) does about heart rate and oxygenation. We compared the sonification against a couple of other candidates that corrected for what we believed might be deficiencies in the original design.

In two studies with the standard pulse oximetry system working alongside the various respiratory sonifications, we showed that our original respiratory sonification performed better than the alternatives and that the advantage was present for all the respiratory parameters RR, Vt and ETCO2. Moreover, when we adjusted for the statistical base rates of events in the scenarios we used to test the sonifications, performance was approximately as effective with the respiratory sonification as for the pulse oximetry system (Watson & Sanderson, 2001). On this basis we proceeded to further questions.

2. Can participants timeshare tasks with sonified monitoring?

In a second study in his PhD thesis, Watson asked how well people can monitor a simulated anaesthetized patient with a visual display (V), a sonification (S), or both (B), when performing a simple arithmetic true-false task at the same time (Watson & Sanderson,

2001). Two populations were compared: clinical anaesthetists and IT postgraduates with no medical experience.

Results showed that IT postgraduates had best patient monitoring in the V and B conditions but best arithmetic task performance in the S condition. On the other hand, trained clinical anaesthetists maintained the same level of patient monitoring accuracy in the S condition as in the V and B conditions but showed best performance on the timeshared arithmetic task in the S condition. Clearly, anaesthetists could not only maintain the highest level of patient monitoring with sonification, but they were able to do other tasks better because their visual attention had been freed up.

3. As workload increases do participants rely more on sonification?

The Watson and Sanderson (2001) research showed a benefit of sonification for tasks *timeshared* with patient monitoring, rather than for patient monitoring itself, where sonification never led to better performance than with visual displays. Would there be conditions under which participants would perform better at patient monitoring with sonification rather than with a visual display?

In her MIT(HCI) thesis, Jennifer Crawford examined whether increased visual and cognitive workload would lead participants to rely on sonification, so that patient monitoring performance might become better with sonification than with a visual display. She reorganized the layout of the experiment so that the patient monitoring screen lay behind the participant and a separate screen carrying the arithmetic task was in front of the participant, as is quite representative for the operating theatre. Participants had to turn around and look directly behind them to see the visual display. The arithmetic task arrived every 5 seconds, in contrast with Watson's 10 seconds. In a closely related honours study, Annyck Savill reduced the arithmetic intertask interval further to 2.5 seconds.

Results showed that reducing the time between arithmetic problems to 5 seconds and even to 2.5 seconds did not lead to an improvement in patient monitoring under sonification, relative to visual displays. There appears to be a limit as to how much information can be extracted from the sonification when the timeshared task is forced-paced (Crawford, Savill, & Sanderson, 2003), an observation that will be followed up in the question in the next section of the paper.

However some benefits of sonification emerged. First, participants working with sonification responded much faster to questions about patient status than those with visual displays or both. Second, we collected video records of participants performing the task. The greater accuracy of the V condition clearly came with a cost. Participants in the V condition looked around at the visual display

more often, for longer on each occasion, and for longer total time than for the B condition (Sanderson, Crawford, Savill, Watson, & Russell, 2003). The pattern of looking at the visual display was sensitive to differences in display modality. We have since used information about headturning and looking in our studies to indicate the level of moment-by-moment need for visual information.

4. Does effectiveness of sonification depend on kind of timesharing?

Operating theatre tasks will vary in nature, so that sonification may help timesharing more in some situations than others. For his honours thesis, John Woodall (supervised by Marcus Watson) investigated whether a manual task timeshared with the patient monitoring task would lead to a stronger benefit of sonification. A manual task was devised based on a label-checking and label-placement task related to the process of blood unit checking and recording. Not only was the resulting label task more manual than cognitive in nature, but it was also self-paced rather than forced paced.

Results of Woodall's study and followup studies suggested that with the self-paced labels task, participants were able to develop a strategy for time-sharing the labels task and the patient monitoring task. Performance on patient monitoring was best in the V and B conditions whereas performance on the labels task was best in the B and S conditions. Participants looked around at the display less often in the B condition than in the V condition. The B condition appears to provide the best of all worlds when the self-paced manual distractor task is used (Watson, Sanderson, Woodall, & Russell, 2003).

How much was the above result due to the manual rather than cognitive nature of the task as opposed to the self-paced rather than forced-paced nature of the task? We developed a self-paced version of the arithmetic task. The results showed no differences between conditions for patient monitoring, but better arithmetic task performance with the S condition (Watson, Sanderson, Woodall, & Russell, 2003). Results for head turning again showed more looks and longer looks in the V than the B condition. This result is similar to the earlier experiments.

The conclusion is that the manual labels task coupled with the B condition gives participants more freedom to reorganize their attentional strategy so that performance at both patient monitoring and the labels task can be at a maximum. These results suggest that sonification will be differentially effective under different conditions.

5. Does operating room noise render sonification less effective?

A key question we are continually asked is whether operating room noise renders sonification less effective than we would wish. Noise

can be related to operative activities such as using the laser scalpel, suctioning, opening equipment or supplies from their protective wrappers, or to extraneous sources such as music. Vivian Shek has examined this issue in an honours thesis in which she compares patient monitoring performance by non-experts with both visual displays and sonification (B) in the presence of either a timeshared labels task, music of different kinds (jazz, rock, or classical), or both the labels task and music.

As expected, performance at patient monitoring appears to be worst when participants must do the labels task and the music is playing at the same time. Interestingly, music appears to have a less distracting effect than the labels task. Performance at patient monitoring is best overall when participants are just listening to music, whereas when participants are doing the labels task, performance is indistinguishable from when they are both doing the labels task and listening to music.

Shek's data also suggest that rock may be more disruptive than either classic or jazz music, possibly because of the vocals in rock. Participants prefer rock over classical music when entering the experiment and when reporting on preferences for music used during the experiment. However participants recognize that it is easiest to perform the tasks when listening to classical than to rock music, which shows that they clearly distinguish their preferences from their judgments of ease of use. Now that we have established our experimental protocol and have some suggestive initial findings, we will soon test whether these effects hold for trained anaesthetists.

6. Will sonification remove the need for alarms?

An original motivation for this program of research was to see whether sonification would partially or completely remove the need for conventional auditory alarms. Alexandra Wee has examined this in her honours thesis where she compared patient monitoring performance where participants use both visual displays and sonification with alarms (BA) or without alarms (B), and where they use just a visual display with alarms (VA). We anticipated that conditions BA and B might support better patient monitoring and timeshared task performance than VA, because of the sonification, and that participants would indicate awareness of changes in patient status as early or earlier in the B condition as in the BA condition.

Analysis of this experiment is ongoing, as we still need to analyse the video records to measure the timecourse of participants' awareness of changes in patient status. Results for patient monitoring and for the timeshared labels task indicate no significant differences between conditions. However in questionnaire responses participants found the BA condition easiest to use, followed by the B and then the VA conditions. In addition, participants found the alarms more helpful in

the VA condition than in the BA condition, indicating that further support beyond the conventional visual displays plus auditory alarms is needed. Whether we can reduce alarms we still do not know.

Summary

Many questions remain in this research program relating to the detection of higher-order properties of the anaesthetized patient and to the ability of sonification to support awareness not only of changes but of deviations from expected changes. All results need to be validated with trained anaesthetists in full-scale simulator and clinical contexts. Our results to date suggest that sonification is a potentially powerful display tool in the safety-critical environment of anaesthesia, and just as the pulse oximetry system has saved lives because of its "early warning" properties, so might respiratory sonification.

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