

Designing Auditory Displays for Team Environments

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Introduction

The goal of this paper is to illustrate the potential use of Ecological Interface Design (EID), with an additional attentional mapping step, to design sonifications for complex real time systems. EID aims to support the human operator's reasoning at different levels of abstraction, so that an interface maps physical functions and measurement to higher order processes. Sonification "the transformation of data relations into perceived relations in acoustic signals for the purpose of facilitating communication or interpretation" (Kramer et. al. 1997). Several successful sonifications have been designed for a variety of tasks from data mining to physiological monitoring (Kramer et al 1997). Most sonifications are designed to be used when the user is fully focused on them rather than as a pre-attentive display. Two examples of sonification where these auditory displays are designed to supplement visual displays will be examined. The first comes from a detailed study of auditory requirements for anaesthetists in the operating room (OR); the second looks at a sonification support for landing multi engine aircraft. Both have been designed with EID modified with attentional mapping to illustrate possible methods, which may reduce cognitive workload for the operators.

Auditory Displays

The design of effective auditory displays that support the human operators of complex systems has received little attention in the human factors literature when compared to the design of visual displays. It is only in the last decade, with the increasing complexity of systems, that the need for well-designed auditory displays has been identified (Patterson, 1990; Woods, 1995). Most auditory displays act only as an adjunct to visual displays, their major role being to direct visual attention. The need for auditory displays to do more than this has been recognised (Woods, 1995; Kramer et. al., 1997; Sarter, 2000) and several approaches are being investigated.

One solution is to make auditory displays more audible and meaningful, which has led to auditory icons and earcons as possible solutions to some problems (Patterson, 1990; Graham 1999). Auditory icons are sounds that are immediately associated with an object in much the same way as visual icons are commonly used in window interfaces. Earcons are more complex as they encode information about the system in a short auditory signal. Localization of sound has also been recognized as an important method of directing visual attention and has led to work on 3-D auditory displays (Nelson et al., 1998, Begault, 2000). Another solution is sonification, which is the transformation of data relations into acoustic relations to display information (Kramer et. al., 1997). Whatever methods are used, the challenges involved in designing auditory displays in complex control environments are substantial largely because of the interactions that arise between tasks being processed in different modalities (Wickens & Hollands, 2000).

In this paper we will focus on the design of sonifications for complex environments. While there are several successful sonifications, it has not yet been possible to develop fully comprehensive guidelines for designing sonifications (but see Barrass, 1997). Many sonifications have been developed with reference to theories of what information should be displayed acoustically, with much of the emphasis on analysing what information should be displayed to support what tasks (Kramer et al. 1997). The difficulties of such an approach may result in poorly conceived displays that are invasive and uninformative (Watson et al, 2000). Work has begun on developing rules for mapping properties of sound but much work is still needed if designers are to effectively use the auditory modality (Barrass, 1996; Sanderson et al., 2000).

Ecological Interface Design and Attentional Mapping

EID stems out of cognitive work analysis (CWA) which is a cognitive engineering approach to identifying requirements for the interfaces of complex real time systems (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). EID uses some of the phases of CWA: work domain analysis (WDA) and worker competency analysis (WCA) in particular (although control task analysis (CTA); strategy analysis; social organisational analysis can be added) and for actual design adds a semantic mapping step (Table 1). It presents guidelines for the development of displays with a key component being the mapping of real world properties to the interface. EID has been successfully applied to the design of visual interfaces for a variety of problems (Dinadis & Vicente, 1996). However until recently EID has only been applied to visual displays (Watson et. al, 1999; Sanderson et. al. 2000). The mapping of data relationships in the auditory domain is not as intuitive or as obvious as it is in the visual domain. There are basic questions such as how to identify the auditory dimension that best represents a data dimension, how to capture changes in data by a change in the auditory dimension, and how to map physical changes into sound changes (Walker et. al., 2000). The steps of EID provide information for auditory displays that in some cases are quite distinct from the advice for visual displays. However this is not enough if EID is to be useful for designing interfaces that include both auditory and visual elements. An attentional mapping phase appears to be needed (Sanderson et. al., 2000). The principles of sonification and EID, if put together, may lead to a much more robust framework for designing auditory displays.

Table 1
Issues for CWA when designing auditory displays.

CWA phase	Issues for auditory displays
Work domain analysis	Identifies domain characteristics and relationships to be displayed in any interface.
Control task analysis	Identifies a profile of ongoing tasks, competition between tasks and <i>attentional profiles</i> across tasks. Auditory or visual display?
Strategy analysis	Auditory displays may extend the range of strategies available.
Social organizational analysis	Indicates where auditory displays might help or hinder coordination between actors, given <i>obligatory</i> nature of most auditory displays.
Worker competence analysis	Indicates characteristics of workers that might point to the effectiveness of auditory elements in interface displays.
EID steps	
Semantic mapping	A framework for judging the information-carrying ability of dimensions of an auditory stimulus based on knowledge of <i>auditory perception</i> .
Attentional mapping	How an auditory display should control attention alongside other interface elements, based on a knowledge of <i>auditory attention</i> .

Exploiting Auditory Attention

To design good auditory displays we need to know about auditory perception and, especially, auditory attention. Audition and vision differ in three fundamental ways. First, sound can be perceived from any direction. Second, sound is transient. Third, there is no equivalent in the auditory modality to visual scanning as an indication of attention (Wickens & Hollands, 2000). Understanding the differences between auditory and visual attentional processes, and their interaction, is crucial in designing effective auditory displays (Sanderson et. al. 2000). An incomplete understanding of these processes may lead to the development of poor displays and may be the reason behind ineffective existing auditory alarm systems. Auditory alarms rely on the auditory modality drawing attention to something that is outside focal awareness because its perceptual processing is obligatory; the sound cannot be shut out. Such intrusive sounds have also been shown to degrade performance at times of high cognitive load (Woods, 1995). There is also anecdotal evidence of people silencing alarms because they are distracting. This can lead to the well-documented “cry wolf” effect where people ignore some important alarms because so many false alarms have preceded them (Woods 1995). Moreover Jones (1999) has also shown that irrelevant sound substantially reduces performance on visual tasks.

In contrast, appropriately designed sonifications reduce the need for alarms and minimise their intrusive effect. However they pose the problem of how to exploit the obligatory processing of sound while minimising the negative effect of the auditory stimulus on performance. The successful design of any continuous auditory display must facilitate the movement of the sound in and out of focal awareness as is appropriate in relation to system status, as illustrated in Table 2 (Sanderson et. al., 2000). Starting with the system in normal state, and with the auditory display being attended to in focal awareness, as other activities intervene the auditory display will move outside focal awareness (arrow 1). When the system then becomes abnormal, the change in the auditory display representing abnormality should be sufficient to bring the auditory display back into focal awareness (arrow 2). From there, the system will move back into a normal state (arrow 3) and the cycle will start again.

Table2
Exploiting Auditory Attention (modified from Sanderson et. al., 2000)

System State	Sound Inside Focal Awareness	Sound Outside Focal Awareness
Normal	Appropriate if attending to the display does not divert resources from critical tasks. Sound must shift out of focal awareness if cognitive resources are needed on another task	Appropriate if system state is inside limits
Abnormal	Appropriate when attention is drawn to critical system state. Must drift out of awareness once action taken and resources are required	Appropriate only after action has been taken and resources are directed to resolve abnormality

Auditory Displays in the Operation Room (OR)

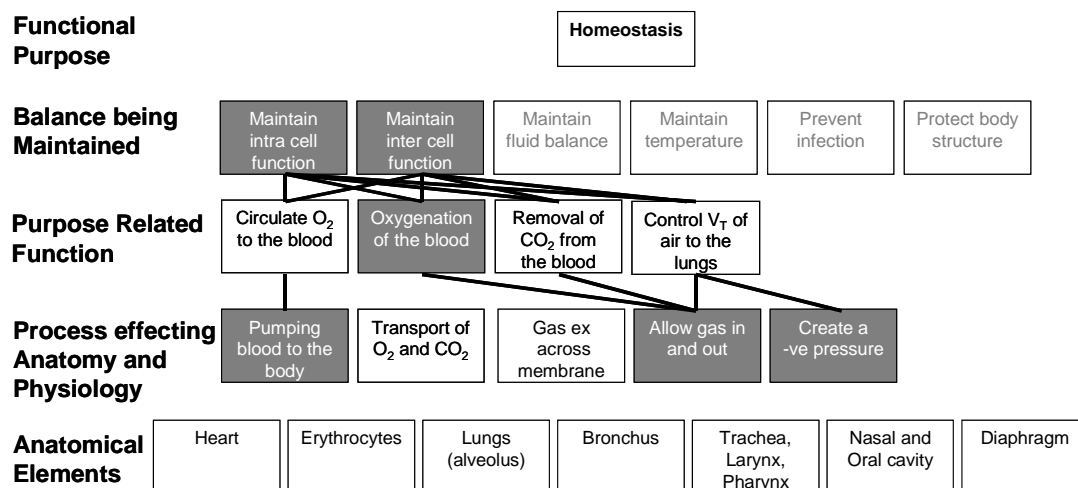
We will now look at the first example of auditory displays developed from EID (Table 1). Anaesthesia in the OR is a highly visually loaded domain, which has led to information displays being presented in serial rather than in parallel. It suffers from high background noise and auditory information introduced in an ad-hoc basis. Watson et al. (2000) investigated anaesthetists' use of alarms at a major

metropolitan hospital in Australia. Of the 42 operations observed, only 3.4% of all alarm sounds caused the anaesthetist to actively make adjustments to change patient state. It was also noted during this study that the anaesthetist responded very quickly to pulse oximetry (an existing sonification in the OR) and often tailored the auditory system to obtain trend information about the patient. Although alarm systems provide very poor support, the Australian Incident Monitoring Study (Webb et al., 1993) found that pulse oximetry was involved in the detection of the largest proportion (27%) of evolving incidents in the OR.

Given such a poor response to the current auditory alarms and an example in place of a very effective sonification, we applied EID to see if we could develop better auditory displays for anaesthesia in the OR. The following phases of CWA were carried out: Work domain analysis of anaesthesia in the OR & the human body at rest; Control task analysis for monitoring displays; Strategy analysis for monitoring displays; and an informal social organisational analysis for team interaction. The EID step of semantic mapping for respiration (sound source, directionality, isomorphism with ventilator etc.) was conducted in conjunction with the principals of attentional mapping (for deviation from normal expired CO₂, range, comparative loudness of pulse oximetry and normal tidal volume of gas exchange etc.).

From the resulting WDA (Figure 1) we were able to identify the essential information for monitoring a patient on the operating table. Since pulse oximetry is already the most important monitoring device, it might be inappropriate to try to replace it. Pulse oximetry uses tempo to indicate the heart rate and pitch to indicate the oxygenation of the patient. With pulse oximetry already providing half the information identified, we designed a second sonification that would provide information about the respiratory status of the patient. Tempo indicates the respiration rate, volume the amount of air entering and exiting the lungs and pitch the expired CO₂. This offered the possible advantage of reducing training time, as anaesthetists are already familiar with pulse oximetry.

Figure 1
Relevant WDA area of the human body at rest (from Watson et. al. 1999)



Both pulse oximetry and respiration sonifications are based on a simple tone sometimes referred to as a “primitive sound” (Barrass 1999). The respiration sonification is designed so that when it deviates from the normal range the display should produce auditory gestalts, which draw the anaesthetist’s attention. As both displays provide information about the patient’s higher order functionality the conjecture is that the sounds can be processed in parallel to quickly identify the patient’s physiological state. Once the patient’s physiological state is identified, we expect the anaesthetist will be able to let the sound

drift out of focal awareness. These hypotheses are currently being evaluated in empirical studies in our laboratory. These two sonifications are not enough to monitor everything that occurs to the patient and to the anesthesia machine; other auditory displays are also required, (Figure 2). Since most of these auditory display are not required in all circumstances it would be anticipated that there would be a reduction in auditory alarms in the OR if such a system was implemented (Watson et. al., 2000).

Figure 2
A possible auditory mapping for anaesthesia monitoring in the OR

Sonification	Pulse Oximetry 1 <ul style="list-style-type: none"> • Tempo = Heart rate • Pitch = Oxygen saturation 	Respiration <ul style="list-style-type: none"> • Tempo = Respiration rate • Volume = Breath volume • Pitch = Expired CO₂ 				
Earcons	Blood Pressure monitoring <ul style="list-style-type: none"> • Current value • Value relevant to last measurement 					
Auditory Icons Alarms & Warnings	Patient temp	System pressure	Volatile gas	System state	Gas supply	Other

Exercise in applying EID to Approach and Landing

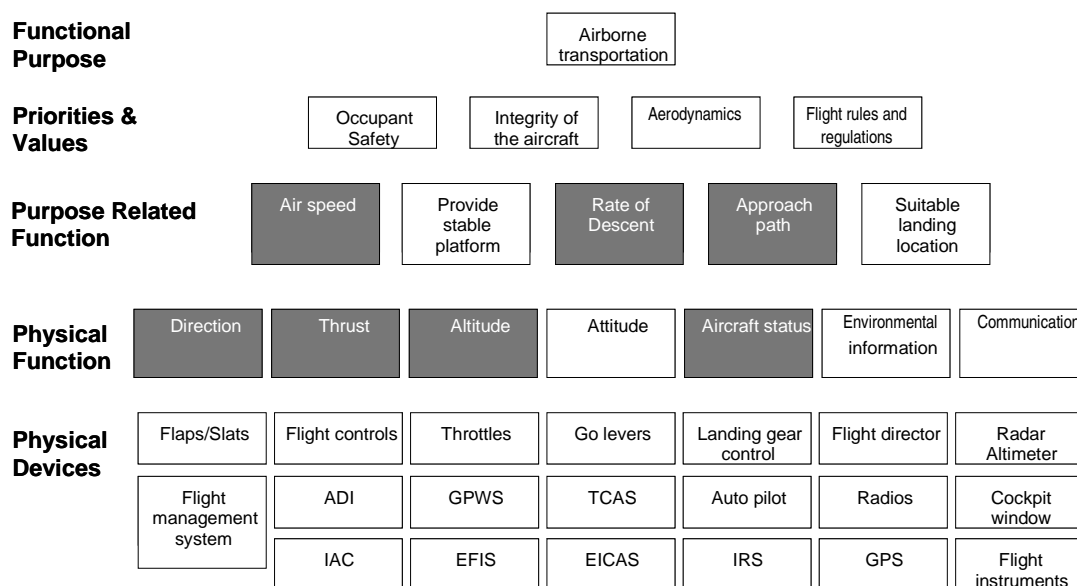
We now take the lessons learned from the physiological sonifications and apply them to aviation. What follows is a hypothetical example that will require further evaluation and possible changes before being a viable display. Prior to the advent of the computer pilots relied heavily on auditory information to fly. The earliest pilots believed it was impossible to fly safely in an enclosed cabin because they needed to feel and hear the environment. Those with gliding experience quickly learned the association between the sound of the air passing over the wing and air speed. In cockpits of large modern aircraft much of the environmental feedback has been lost and is now replaced with visual displays. This has led a visually overloaded domain with high background noise, similar to the experiences of anaesthesia. To complicate this further there is a higher level of automation in the cockpit than in the OR and therefore the problem of visually monitoring has increased (Sarter, 2000). This has led to problems associated with visual displays which require serial processing. Lastly auditory displays used in the cockpit also tend to suffer the same problems found in anaesthesia and nuclear power control rooms (Woods, 1995, Sarter, 2000).

In this example we only tackle part of the auditory display problem as an example of how sonification might be used and guided by EID. This is not the first time auditory displays have been used to assist landings; the earliest landing aids were auditory. Radio landing beacons provided auditory landing signals to support night landing during WWII. Pilots would hear one signal indicating they were drifting left and another when drifting right on their approach. This was known as “flying the beam”. Since then further variants have been designed to support instrument landing approaches, however much of this information is now displayed visually rather than acoustically.

We examined approach and landing task and conducted a limited version of CWA. The phases of CWA carried out were: the Work Domain Analysis of landing approach and Control Task Analysis for the monitoring of visual & auditory displays. The EID step of Semantic Mapping for information to sound dimensions (ranges within dimensions have not been defined) and Attentional Mapping for deviation from normal (for air speed, altitude, throttle setting etc.) were given greater attention. From the WDA critical information appropriate to landing was identified and is highlighted in Figure 3. The

selected functions have been informally verified by subject matter experts and pilots as essential for landing. As for the anaesthesia example, only higher order properties that can currently be measured have been included in the design. Two major features were identified from the WDA and the CTA: first a group of functions related to spatial location (altitude, air speed and direction) and second a group relating to engineering function (control of thrust and automation). For the semantic mapping, a sonification needs to be mapped on natural association linked to these variables. We will look at these two groupings in turn.

Figure 3
WDA of approach and landing. Highlighted boxes indicate key information for display

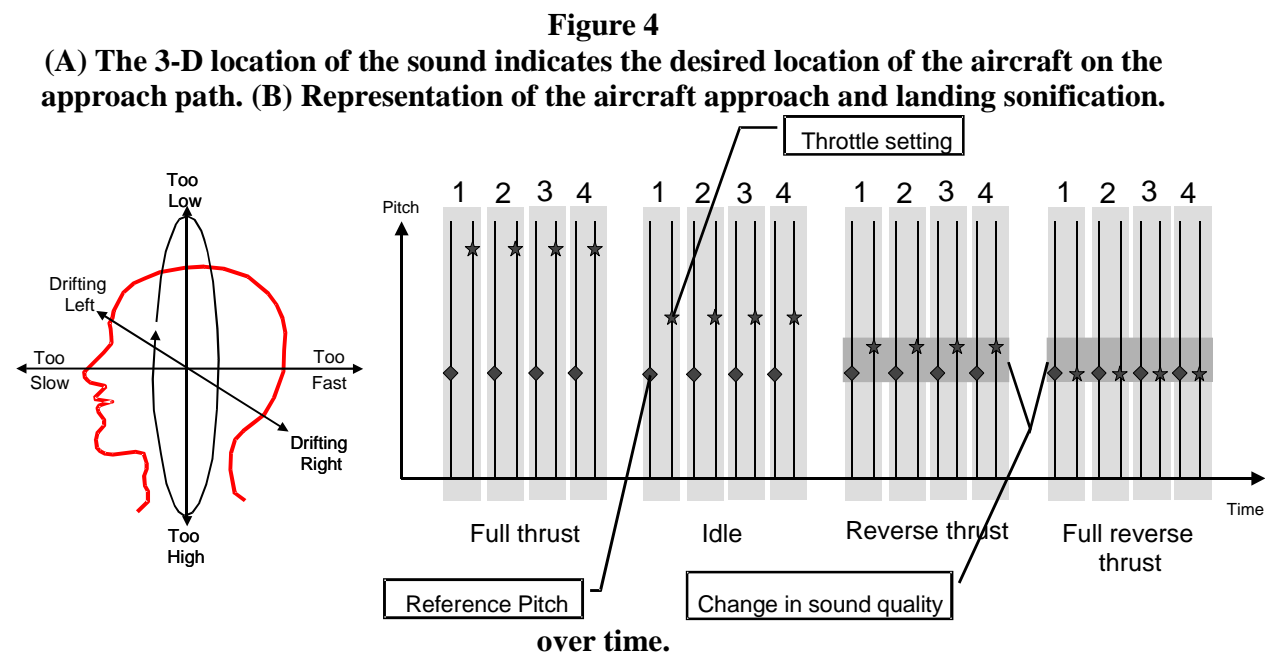


The first group all relate to spatial location, so a natural association can be produced by using the location of the sound to indicate equivalent desired spatial states. Research in three-dimensional (3-D) auditory displays has indicated that we perform tracking and locating tasks with both visual and auditory displays better with than visual alone (Bronkhorst et al., 1996; Nelson et al., 1998). If we now look at the approach a landing task as a pursuit task then we could expect similar levels of success. Figure 4A describes the spatial mapping between the position of the sound and the relevant state of the aircraft on the approach path. The sound is spatially located where the center of the flight approach path lies relative to the aircraft. If the aircraft is too low along the approach the sound will be heard above. In a more complex example, if the aircraft is too low, drifting right of the approach and descending with a high air speed, the sound will be heard from behind, above and to the left of the crew. Any non-central location warns the pilot something is wrong and absolute location informs what is wrong. The pilot can rectify this by existing visual guidance or by flying towards the sound while conducting visually demanding tasks.

The sonification could be used to carry other important information about the aircraft's state. It could give information about factors that can affect current spatial location, such as automation and throttle setting. Sarter (2000) indicated that the visual cues that indicate changes in automation setting are poor and may be missed by traditional visual scanning methods. She states the need for other modalities to support attention allocation in order to keep the pilot in the loop.

With these principles in mind we can now explore the semantic mapping of sound. Figure 4B displays the different properties of sound mapped over time. Air speed is indicated by the time between

iterations of all four engines (the tempo of the sound); Engine setting is indicated by the order (1 to 4). Throttle setting is indicated by relative pitch – the difference between a basic sound (see diamond) and a sound representing the current setting (star). Idle is a harmonic interval related to the baseline sound. Higher sounds represent forward thrust; lower sounds reverse thrust. Reverse thrust settings are also highlighted by a reverberation in the sound. The type of flight mode is indicated by the timbre of the sound. Overall the design aims to inform the crew not only about the current settings and changes from those setting but also about the limitations and affordances of the current configuration.



Conclusion

We are not proposing that the auditory display presented here should be adopted as a landing display in its current form. The example given is simply an example of how sonifications might be developed for complex environments. As noted, considerably more investigation and testing would be required to design an auditory display of this kind that would be effective in today's cockpit. All steps of the CWA should be carried out in order to avoid conflicts with existing systems and to develop cohesive semantic and attentional mapping. This paper has highlighted how sonification provides information about the changing state of the system rather than simply directing attention when a boundary limit is breached. With further work the development of auditory displays using EID (modified with attentional mapping) for the glass cockpit may reduce perceptual-motor workload and cognitive workload experienced by crews. Prior to achieving this there is still a great deal of research required on auditory attention and role of attention in an operator's use of integrated auditory displays.

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