FROM INFORMATION CONTENT TO AUDITORY DISPLAY WITH ECOLOGICAL INTERFACE DESIGN: PROSPECTS AND CHALLENGES

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We examine how Ecological Interface Design (EID) might better bridge the gap from analysis to design by taking different modalities into account. Whereas almost all previous research using EID has focused on visual displays, attempts to extend the use of EID to non-visual modalities have revealed hidden assumptions that need to be made explicit and questioned. In this paper we explore the potential for EID to support a systematic process for the design for auditory displays, illustrating our argument with the design of auditory displays to support anaesthesia monitoring. We propose a set of steps that analysts might take to move more deliberatively and effectively from analysis to design with EID.

INTRODUCTION

Over the last 25 years, cognitive engineers have paid considerable attention to the design of visual displays. A particular concern has been to produce approaches or methods that will help design teams move in an auditable manner from a problem statement to information requirements, and from information requirements to the physical form of an information display (Burns & Hajdukiewicz, 2004; Bennett, Nagy and Flach, 1997). Far less attention has been paid to the design of displays in other modalities, although examples are starting to appear. There is much research on multi-modal displays and interfaces, but very little of it is from a cognitive engineering point of view.

The goal of this paper is to present some of the challenges in moving from analysis to design in the case of auditory displays, and to show how the challenges might start to be overcome. We outline some of the issues involved, using the development of auditory displays for patient monitoring during anesthesia as a case study. Some of the difficulties—and their possible resolution—reveal some of the hidden assumptions of Ecological Interface Design (EID: Vicente, 2002) and point to how EID might be extended and strengthened. In this way EID might more effectively guide designers from analysis to design.

Throughout the paper we illustrate our points with auditory displays that have been developed to support monitoring of anesthetised patients in the operating theatre (OT) (Sanderson, Watson, & Russell, 2005; Watson & Sanderson, 2004; Watson & Gill, 2004).

EID AND A VISUAL THESAURUS

The principles of EID can be briefly summarised as follows (see Figure 1):

- The interface content should represent all information in an abstraction hierarchy model of the work domain. This is to support knowledge-based behaviour—reasoning symbolically from first principles when rules or skilled routines cannot be used.
- Perceptual forms used should map directly into work domain constraints. This is to support rule-based behaviour—providing signs that point directly to appropriate actions.
- The interface should provide a capability for direct manipulation. This is to support skill-based behaviour—providing the means for behaviour to be guided automatically by space-time signals.

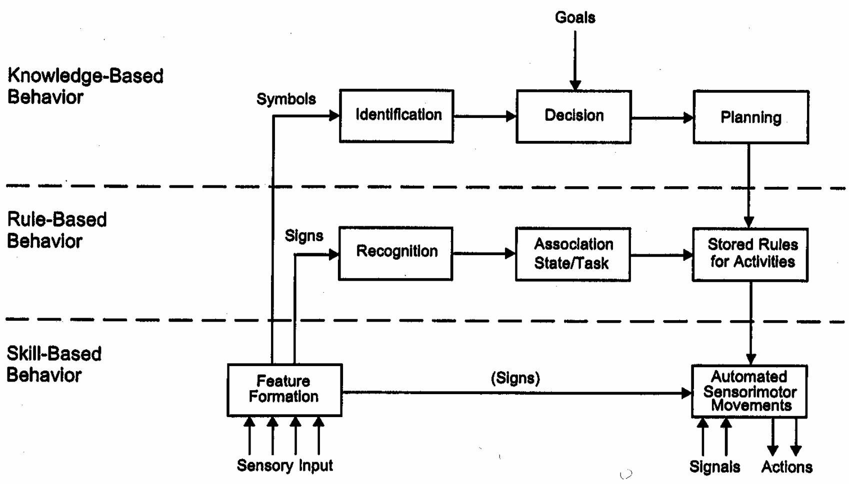

Figure 1: Skills, rules and knowledge based behaviour framework. Auditory displays developed with EID would be required to support behaviour at these levels of cognitive control (from Vicente, 1999)

The principles of EID therefore focus on two aspects of the constraints that operate on the human operator's activity—the structure of the work domain and the kind of cognitive control that is exercised over activity. With these tools, the goal is to provide a "visual ecology" by mapping the goal-relevant constraints of the work domain onto visual forms. The latter process is called the "semantic mapping" process.

Burns and Hajdukiewicz (2004) present a process for semantic mapping by mapping a set of visual primitives to work domain properties. A work domain analysis (WDA) provides a description of the functional structure of a work domain, including an inventory of variables and their means-ends relation to each other. From the work domain analysis, the range of variation and the critical values for each variable can be identified. A unique focus of EID is to show higher-order properties that may have to be derived from lower-order values (Reising & Sanderson, 2002a). Simple visual forms can represent these properties. Examples are the single bars to represent distance, time, and energy values in Figure 2.

Next, relationships between multiple variables are highlighted through visual devices such as connections, containment, grouping, and so on. Examples are the connections between the distance and time bar or between the energy bars in Figure 2. Finally, how-why or means-ends relationships are highlighted through visual devices such as connections, ordering, positioning, and so on. A higher order property may be visually connected with its lower-order variables. Examples are the relation between energy in and its means, the fuel injection rate.

When put in the broader context of cognitive work analysis, the use of the skills-rules-knowledge (SRK) framework and the use of the abstraction hierarchy represent just two of the five kinds of constraint that operate on human operator activity—the constraints of cognitive control and of the functional structure of the work domain (top and bottom rows of Figure 3.

As we will see, the design of auditory displays requires us to stretch beyond these two constraints to the other three shown in Figure 3.

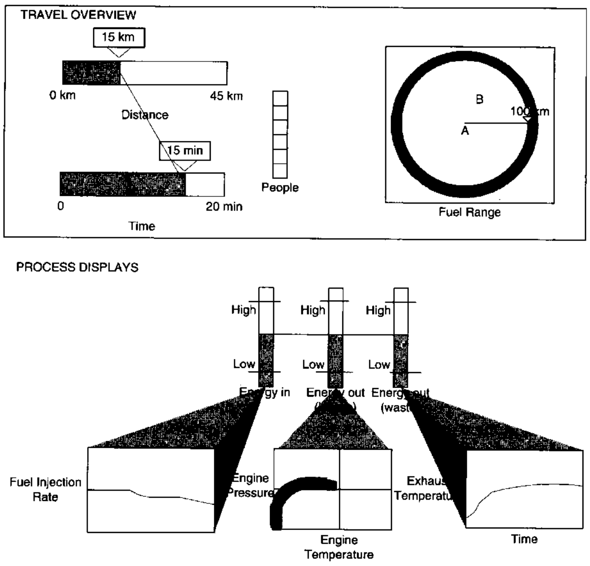

Figure 2: Results of semantic mapping for work domain of driving (Burns and Hajdukiewicz, 2004).

Researchers have often noted the serendipitous use of auditory information by human operators in process control. However relatively few researchers have investigated how this usefulness might become a formal part of the design, although some studies have been done. An important question is whether semantic mapping can be done within the auditory domain so that auditory support moves from being (1) focused on alarm design only or (2) serendipitous, to being intentionally designed.

CWA phase	Information provided about	Modality issues
Work Domain Analysis (WDA)	Why the system or work domain exists, the flow of information or value through it, its functions, processes, and objects.	Are the properties and relations of the domain better represented in one modality or a combination of modalities?
Control Task Analysis (CTA)	What needs to be done in the work domain for it to achieve its functional purpose.	When and why should attention be captured and sustained, and which modality suits control needs best?
Strategy Analysis (SA)	Different ways in which control tasks can be carried out.	Does a strategy change involving a modality change lead to desired change in cognitive control?
Social-Organisational Analysis (SOA)	How work is shared across multiple actors and how they coordinate efforts.	Who needs to be aware of information, and when?
Worker Competencies Analysis (WCA)	Cognitive control needed for control tasks, distinguishing SBB, RBB, and KBB.	Does competence change with a modality change and what experience, training, or acuity is needed?

Figure 3: Phases of Cognitive Work Analysis, indicating information provided at each phase and modality-related issues addressed at each phase (based on Sanderson, Anderson, & Watson, 2000).

Taking a leaf from EID for visual displays, the goal is to determine if it is possible to “reverse engineer” an acoustic ecology that will support the human operator and supplement visual displays in a helpful way. (Walker & Kramer, 2004). Can we apply EID to the design of auditory displays?

EID AND AN AUDITORY THESAURUS

To examine the possibilities, we start with outlining the different kinds of auditory displays (Kramer, 1994).

An *auditory icon* is a discrete sound that is an image of the thing it is referring to. An example is the sound of a door closing to represent that a person has left an online meeting. An auditory icon is often created from a sample of a real-world sound and it bears a semantic relationship to its referent.

An *earcon* is a discrete sound that is a member of a set of sounds that are related to each other through a syntactic structure. An earcon tends not to have a direct semantic association with its referent. An example is a set of tone sequences that indicate that BP is higher than normal, normal, or lower than normal by giving the current reading a pitch that is higher, equivalent, or lower than an immediately preceding standard pitch to represent normal.

An *audification* is a direct translation of physical energy from some source in the world into an audible sound. An example is a stethoscope, where very low intensity breathing and heart sounds are amplified to be clearly heard.

A *sonification* is an indirect mapping of a digital representation of information from some source in the world into selected auditory dimensions. An example is the heart monitor (pulse oximetry system) where heart rate is a smoothed average of EEG inter-beat intervals and percentage oxygenation of arterial blood is represented as pitch.

To apply EID to the design of visual displays, the usual place to start is extracting the information that needs to be known through a WDA. We can then move through the stages suggested by Burns and Hajdukiewicz (2004). For each step, there is quite a lot of information in the psychoacoustic literature, even though it tends to be based on unrepresentative laboratory experiments (see Neuhoff, 2004 for a discussion of this).

- **Range of variation and critical variables.** Burns & Hadjukiewicz’s (2004) first step for semantic mapping is to take individual variables and map them to auditory parameters capable of representing the range of variation required, and capable of representing critical values. Walker’s (2002) work on how directions of measured values should be mapped to polarity of auditory dimensions is relevant for this, as is the work of Anderson and Sanderson (2004) on the calibration of auditory dimensions to represent measured values from the anesthesia domain. Research relating to how the mapping can be designed so that high, normal and low ranges can be discerned, or so that any departure from normality is acoustically marked, is also relevant here.
- **Relationships between multiple variables**—Burns and Hajdukiewicz’s (2004) second step in semantic mapping involves showing the goal-relevant relationships between multiple variables. Here a consideration of auditory streams or auditory objects becomes important (Bregman, 1990). For comparisons, is it better to map variables to be compared onto a single auditory stream or to divide them across multiple auditory streams (Anderson & Sanderson, 2004)? Further issues are what the basis for comparison might be. For example, Watson and Gill (2003) have created earcons to display intermittently-recorded blood pressure (BP) measures. By successively providing a tone associated with normality, a tone indicating the last BP reading and a tone indicating the current reading, the appropriate comparisons can be made.
- **Means-ends relations**. Burns and Hajdukiewicz’s (2004) final step is to display means ends relations. Many of the techniques used to show relationships between multiple variables can be used, including the idea of configurality—where individual dimensions of a sound are mapped to low-level variables in such a way that the overall impression that emerges is semantically related to higher-order variables (eg urgency, tranquillity, etc).

In addition to performing the above mappings, it is tempting to try to map kinds of auditory displays to different levels of cognitive control or different levels of abstraction. However there is no simple mapping of kinds of auditory displays to SRK or to levels of abstraction. The same display can support reasoning at any level. In the visual domain, Rasmussen (1986) shows that the same circular dial reading can be a signal for tracking, a cue to apply a well-known diagnostic rule, or, given its context, an inconsistency whose cause needs to be deduced. The context rather than the format of the display itself dictates the kind of reasoning applied to the display.

However if we are to design to support SRK, we need to consider whether some kinds of auditory display would support skill-, rule-, or knowledge-based behaviour (SBB, RBB or KBB) better than others, just as analytic geometry representing heat exchange equations supports better knowledge-based reasoning about heat exchange than a picture of a heat exchanger (Reising & Sanderson, 2002).

SBB is facilitated by displays that have space/time signals. Auditory displays that map their inherent temporality to system properties will be particularly effective, such as sonification and audification. For example, the cumulative amount of gas going in and out of a patient’s lungs (cumulative tidal volume or Vt) may be represented as sound intensity in a sonification, so the sonification is loudest when the patient’s chest is most expanded and quietest when the patient’s chest is least expanded (Watson & Sanderson, 2004). In some cases, by converting a representation from the visual to the auditory modality, we may move it from being RBB to SBB. Spatialized audio can support SBB in inherently spatial domains, but where a phenomenon is not inherently spatial the mapping to sound is more difficult.

Auditory displays that attract attention and that constitute a sign to act will be effective for RBB—the auditory pattern indicating certain action. This is where alarms have been used for years, often with less effective results than desired, but more subtle auditory patterns than alarms are possible to indicate more subtle distinctions. For example, using physiological sonification (Watson & Sanderson, 2004), a rapid heart rate at relatively low pitch plus rapid quiet breaths at a relatively low pitch is a pattern of vital signs that will be recognised as shock, with rule-based treatment pathways following. If there is no immediately obvious reason for shock (such as blood loss associated with trauma) then the physiological sonification will support KBB.

CHALLENGES FROM AUDITORY MODALITY

The above steps can be taken to move from requirements to design of an auditory display, but taking the above steps alone may lead to a display that is intolerable in its context (Edworthy, 1998). We discuss why this is the case and indicate where further phases of cognitive work analysis (CWA) than those typically used in EID may provide further help.

Auditory displays have different properties from visual displays. First, auditory displays tend to be *ubiquitous* rather than *localised*, in the sense that they can be heard from any orientation. A listener usually does not need to orient themselves to the sound in order to hear it, the way a viewer must orient their eyes to a visual display. Second, auditory displays are *obligatory* rather than *optional*, in the sense that they are usually sensed whereas the viewer of a visual display may opt to "turn off" the display by looking away from it. Finally, auditory displays tend to be *transitory* rather than *persistent*, in the sense that they usually have a start and end point in time, whereas a visual display can more easily display information persistently. Using these distinctions, we see that EID does not provide guidance on some issues that are more pressing for auditory displays than for visual displays:

First, the analysis of who should use a display is not a formal part of EID. A visual display is localised and optional and so the issue of inappropriate capture of attention to the display is not addressed. An auditory display, however, is ubiquitous and obligatory, and so will impinge upon other people within earshot. An analysis of whom the auditory display should reach needs to be handled formally. CWA may provide analytic tools for this in social-organisational analysis and solutions may involve earpieces and other forms of selective or optional delivery.

Second, the analysis of when a display should be displayed is not a formal part of EID. Ubiquitous and obligatory displays will occur at the same time in a way that visual displays do not, and will compete for attention. EID for visual displays has considered the temporal and spatial separation of displays (Burns, 2000) but not the problem of potential occlusion that can occur in the auditory space. CWA may help us solve this by putting control task analysis and strategies analysis to work on when an auditory display should occur, and psychoacoustics help us divide the acoustic space in a manner that auditory masking or interference does not occur.

Third, the analysis of when a display should be attended is not a formal part of EID. It is assumed that a visual display will be attended when the need for information is felt, despite being localised and optional. An auditory display, being ubiquitous and obligatory, could in principle be continuously attended, but in practice this would be intolerable. Instead, an auditory display could be intermittent, drawing attention when it appears, or it can be continuous but designed in such a way that it draws attention to itself only when functionally significant changes are sensed. The commonly discussed "semantic mapping" phase of EID may need to be supplemented with an "attentional mapping" phase that solves this problem.

Fourth, how the display should map the temporal properties of the event with respect to the time period of the display is not a formal part of EID. Visual displays allow easy examination of a historical record through persistence—they are available whenever the viewer cares to look. Auditory displays make this harder, as the displays themselves exist in time and so are transitory. Extracting information is locked to particular points in time and relies upon memory. A consideration of the load on working memory of retaining information is not a formal part of EID. It is a kind of worker competency, but not one that has been considered when that phase of CWA is usually discussed. A consideration of this issue can lead to an allocation of kinds of auditory displays to variables according to the frequency of change of a signal or variable. In the OT, continuously measured vital signs associated with pulse oximetry and respiration may appear in sonification, continuous or intermittently-measured vital signs such as blood pressure in sonification or earcons, and intermittently measured vital signs or states in earcons or auditory icons.

Fifth, the sensory context of the work domain needs to be taken into account. What is the visual, auditory, and haptic environment in which the new display will be placed? This involves taking a step beyond work domain analysis and so is beyond current CWA.

CONCLUSION

In summary, when moving from information requirements to design using auditory displays, it is possible to apply the principles of EID and so help to bridge the gap between analysis and design. However EID brings with it implicit assumptions that the display will be visual that become exposed when designers are working with an auditory display instead. The end result may not take into account aspects of the work domain and the work context that are important.

We propose that to complete the analysis needed, and to strengthen the movement from information requirements to design when auditory displays are being considered, designers should consider (1) who should use a display, (2) when the display should occur, (3) when the display should be attended, (4) how the display maps temporal properties of the world, and (5) the sensory context of the work. Some of these considerations can be helped with the existing phases of CWA. Others will require further extensions.

A design process based in EID that takes into account auditory displays as well as visual displays needs to consider the following, in order:

1. Who needs to keep track of which part of the work domain
2. What is the sensory context of the work domain (visual, auditory, haptic)

3. What variables and relations need to be displayed?
4. When and how fast to variables change and how should this be mapped to displays?
5. What level of cognitive control is needed?
6. Which modality or modalities would be best?
7. Is there an existing design pattern that would fit the above requirements
8. For visual displays
    - Provide framework for visual displays
    - Provide details in a process like that of Burns and Hajdukiewicz (2004)
    - Test the results
9. For auditory displays
    - Perform attentional mapping across different people in the workspace
    - Perform attentional mapping for the primary person who will monitor
    - Test the results
10. Test the combined effect.

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