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PERCEPTUAL CONTROL THEORY AND ECOLOGICAL INTERFACE DESIGN: LESSONS LEARNED FROM THE CONTROL DISPLAY UNIT

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The purpose of this research was to assess the applicability of Perceptual Control Theory (PCT) and Ecological Interface Design (EID) to the radio communication domain, and to perform an analytical evaluation between PCT and EID using the Control Display Unit (CDU) interface as a vehicle. A PCT-based analysis of the pilot-CDU interactions was performed and an Abstraction Hierarchy representation of the radio communication domain was developed. Two interface designs followed and their effectiveness was assessed analytically by judging their ability to support tasks under normal and abnormal circumstances. The results suggest that both interfaces permit radio exchanges to be performed under normal operations. Also, both interfaces lead to the detection of technical failures and environmental concerns impeding successful radio communication. However, the PCT-based interface did not support diagnostic activities related to disturbances of a technical and environmental nature in the communication work domain, whereas the EID interface was able to support diagnostic activities for disturbances of environmental sources for the given task situations.

INTRODUCTION

Systems analysis techniques have been viable tools for human factors specialists to analyze and design human-machine systems. The nature or complexity of the system under study often becomes the determining factor of the type of analysis yielding the most effective interface supporting operators in normal and abnormal working conditions.

This paper reviews two different interface design framework, Perceptual Control Theory (PCT) (Farrell and Chery, 1998), and Ecological Interface Design (EID) (Vicente and Rasmussen, 1992). PCT models the human's interactions with the environment while EID focuses on the representation of work domain's functional and structural constraints.

This work involves the development of two interfaces based on the principles of PCT and EID using as a vehicle the Control Display Unit (CDU) to compare the two approaches. The PCT and EID based interfaces were designed and their effectiveness was analytically evaluated.

A brief description of the CDU layout, functions, and current areas of concern are given in the next section. Then, the theoretical foundations of PCT and EID are summarized, followed by a description of the analyses that were carried out, and the implementation of the design requirements in an interface. Finally, the procedures used to perform the analytical evaluation are presented, followed by the results obtained, and a discussion.

Control Display Unit: Background

A Control Display Unit (CDU) is the interface to the flight management subsystems of aircraft and assists in navigational, mission planning, and radio communication activities. The current CDU of the CH-146 Griffon Helicopter is comprised of an electroluminescent display screen with adjacent keys and an alphanumeric keyboard.

CDU: Areas of concern. The current CDU interface has brought some issues of concern, such as increased pilot workload, to the attention of human factors specialists as well as to the Griffon operational community. Those concerns mainly involve the communication and navigation functionalities of the device as well as some general interface design issues. Improper feedback from the CDU to the pilot, and function selection involving lengthy initialization of unwanted features, among others, were all issues that need to be resolved. It is thought that an interface based on the principles of feedback – by means of a PCT analysis – and/or visibility – by means of an EID analysis – could be an attempt to mitigate some of those concerns.

Perceptual Control Theory

Perceptual Control Theory (PCT) is a framework for modeling human behaviors taking its premises in the engineering concepts of classical control theory. PCT's core tenet is that all behaviors result from the control of perceptions (Powers, 1973). Once the operator's goal states and current states are disclosed, behaviors become predictable since the impetus for action lies in the magnitude of the error signal. Moreover, PCT is hierarchical in nature where behaviors become lower-level goals and lower-level perceptions become higher-level sensory information (see Figure 1).

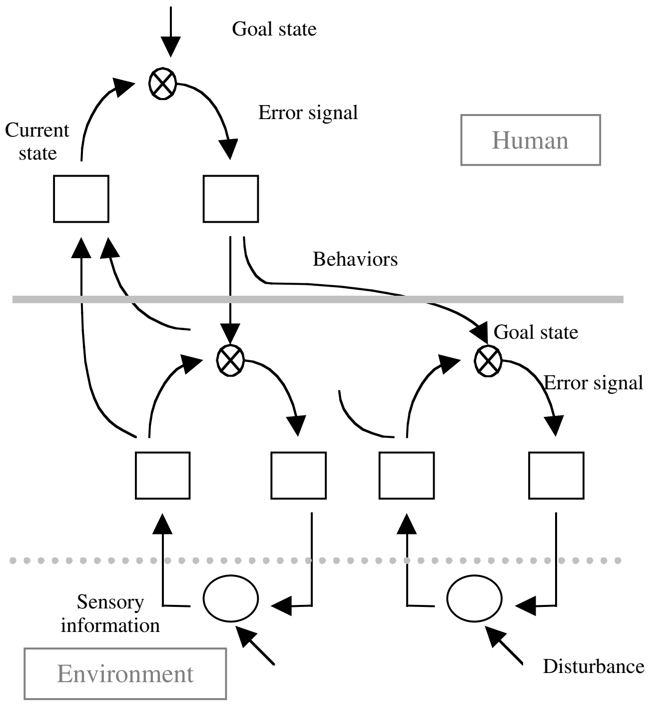

Figure 1. Hierarchy of the Perceptual Control Theory loops.

Implications for interface design. PCT, having an error-correcting basis, attempts to assure the implementation of feedback at all hierarchical levels. Using PCT's tenet, an analyst can design displays that lead to necessary information allowing operators to generate perceptions to closely meet their desired states. By the same token, controls can be designed to give the possibility of compensatory behaviors to occur given the operators' goals (Farrell and Chery, 1998). The design specifications then become geared toward the minimization of the perceptual error.

Ecological Interface Design

Ecological Interface Design (EID) is a framework for designing interfaces for complex human-machine systems that provides the informational basis able to support operators' skills, rule, and knowledge based behaviors (Vicente and Rasmussen, 1992). It bases its core within ecological psychology and stresses the role of the environment in constraining human behaviors. EID attempts to externalize the structural and functional properties of the work domain onto the perceptual features of the interface. Such properties are yielded through a work domain analysis using the Abstraction Hierarchy (AH), as a tool, which leads to a multi-level structural means-end representation of the work domain under study (Rasmussen, 1985). Moreover, EID prescribes design principles for the development of visual representational forms to be instantiated in the interface to exploit human perceptual skills (Vicente and Rasmussen, 1992).

Implications for interface design. The information content specifically conveyed by EID makes it effectively applicable for domains where unanticipated events are prevalent and potentially hazardous. Given that the informational basis relays causal and functional constraints, the interface does not become bounded by particular operational procedures, and hence, could accommodate situations that were unanticipated by designers (Vicente and Rasmussen, 1992). Also, the EID framework provides a systematic methodology for structuring the interface content by having different abstraction levels linked via a structural means-end relationship. Such a methodology has been seen as particularly useful for the support of problem-solving activities.

METHODOLOGY

This section briefly describes the analysis required by each framework, the implementation of the design requirements in the interface, and the analytical evaluation performed.

PCT-based CDU Interface

Analysis. The PCT-based analysis technique tables were used for the development of the CDU design (Farrell and Chery, 1998) (see Table 1). The analysis yielded a list of display and control requirements for the CDU interface at each level of the PCT hierarchy.

Table 1. Example of a PCT based analysis table.

	Error signal	Decision-making processes	Behaviors	Interface controls	
Goal					Environ-mental variable
	Perception	Integration processes	Sensory information	Interface displays	

Interface design. PCT provides the information requirements for interface design, and suggests that the information should be integrated in a fashion that mirrors the model's hierarchy while feedback should be integrated at all levels. However, PCT does not prescribe a systematic way to convey the informational requirements in a representational form. Several human-computer interaction design principles from the Department of Defense design criteria -- human engineering standards (MIL-STD-1472E) (Department of Defense, 1996) were followed for the design. The resulting PCT-based interface is presented in Figure 2.

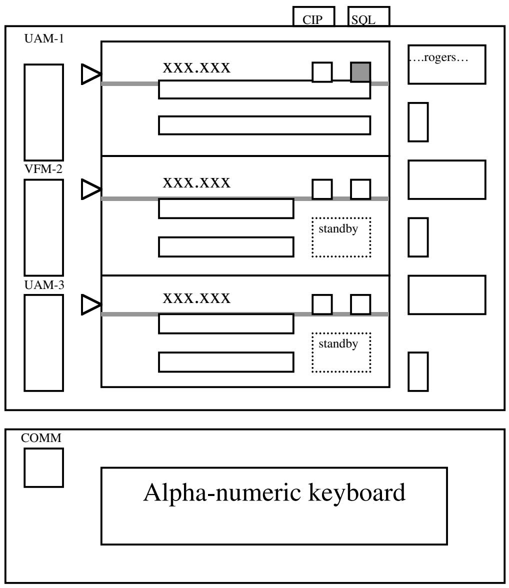

Figure 2. PCT based CDU interface for communication management.

EID-based CDU Interface

Analysis. An abstraction hierarchy was developed for the radio communication work domain. Five constraint levels specific to this work domain were developed and are presented in Table 2.

Table 2. Structural Means-End Levels for the radio communication domain.

	Work Domain
Purpose	Permit voice communication between remotely located parties
Communication Theory	Entropy at source, channel, equivocation, noise, encoder, decoder, entropy at destination
Principles of Radiophony	Signal transduction, frequency generation, interference generation, modulation, radiation, propagation, extraction, refraction, demodulation, absorption, attenuation, interference reduction, frequency conversion
Equipment	Microphone, electric source, ionosphere, terrain, airspace, antenna, filter, modulator, demodulator, oscillator, correcting network, speaker
Physical Form	Location, appearance, and physical connections

Interface design. The three EID principles presented below were followed for the interface design of the CDU:

- Representation of the work domain in its structural means-end relationships
- One-to-one mapping of the work domain semantics into a visual form, and
- Allowing operators to directly act on the display (direct manipulation).

The information requirements obtained from the abstraction hierarchy were then implemented in the interface (shown in Figure 3) and its design followed the above guidelines.

Analytical Comparative Evaluation

The capabilities of the interfaces to support normal and abnormal radio exchanges were assessed by investigating the effectiveness of the interface information content. By effectiveness, it is meant that the informational basis can support an operator leading to improved performance or aid in the execution of a task which could not have be done otherwise (Rouse, 1984). The means by which effectiveness was assessed was through an analytical evaluation. Rouse (1984) suggests that analytical evaluations are used for the assessment of the interface functionality (delineating the interface capabilities) whereas empirical evaluations aim at assessing interface usability (delineating how the interface capabilities are implemented). The necessity to perform analytical evaluation to investigate interface effectiveness before the assessment of understandability and compatibility issues (relating to interface form - via empirical evaluations) insures the development of a functional interface (Rouse, 1984).

The technique used to carry out the evaluation was a cognitive walkthrough which aids in determining the support provided by the interface for operators to perform their tasks (Lewis and Warton, 1997). Tasks were taken from a realistic mission scenario and were grouped under three different categories: radio exchanges performed under:

- normal operations,
- abnormal operations – technical concerns (instances where devices in the work domain would fail to operate), and
- abnormal operations – environmental concerns (instances where meteorological and/or terrain features would impede successful radio communications).

RESULTS

The results from the evaluation are summarized in Table 3.

The PCT based interface was able to support normal operations of the task situations studied. It could also support the detection of problems of a technical or environmental nature, but did not allow their discrimination to be made (the "x" symbol in the table signifies the inability to discriminate the nature of the abnormal situation). Thus, no diagnostic activities could take place for those particular task situations.

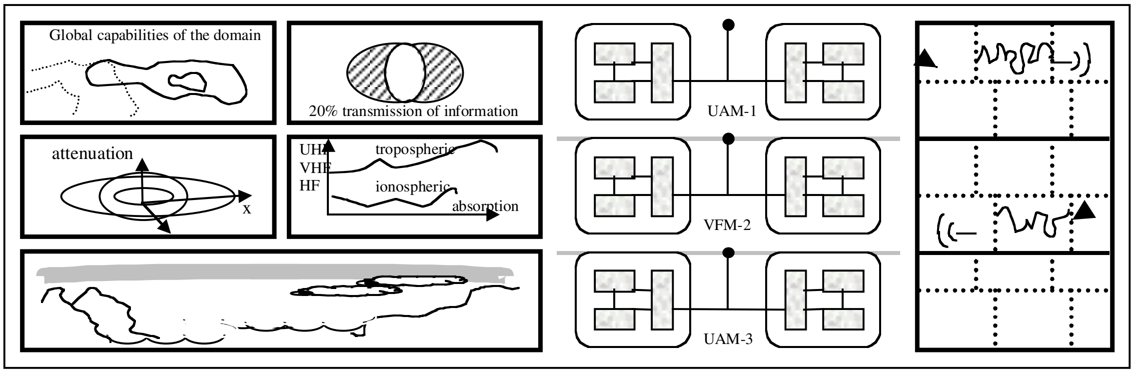

Figure 3. EID based CDU interface for communication management.

The EID-based interface was able to provide support for the normal task situations studied. It also provided information that could support the detection of problems. Contrary to the PCT interface, the EID design conveys information that could permit the discrimination of technical or environmental problems. However, it did not support the diagnosis of technical failures but did so for environmental disturbances.

Table 3. Results of operational capabilities of PCT and EID based CDU interfaces.

	Normal Situations	Abnormal Situations: Technical Concerns		Abnormal Situations: Environmental Concerns	
		Detection	Diagnosis	Detection	Diagnosis
PCT based interface	√	x		x	
EID based interface	√	√		√	√

DISCUSSION

Normal Operations

The task situations illustrating normal operations were supported by both interfaces. However, the PCT interface seems to demonstrate easier procedures due to its user-friendliness and its compatibility with current standard operating procedures.

For the EID interface, the normal conditions of the work domain were made explicit on the display; however, the interface did not intuitively prescribe the user particular types of action needed to be performed to establish a radio link. Training would be necessary if the EID interface were to be used as is.

Abnormal Operations – Technical Concerns

Both interfaces supported the detection of technical failures although they did not support any diagnostic activities with respect to the fault. The PCT interface did not support the diagnosis of technical concerns since assumptions were implicitly made early in the analysis that restricted the analysis to setting radio links only. It can be shown, a posteriori, that a PCT model for diagnosis may be used alongside the original model in order to ensure that all necessary diagnostic information is contained within the original model.

With respect to EID, the finding is also not surprising since the Abstraction Hierarchy (AH) modeled radio communications as the work domain and not the equipment of the domain. If an AH was done for each individual piece of equipment involved in radio communications, troubleshooting for their functioning would be feasible.

Abnormal Operations – Environmental Concerns

The PCT interface did not support the diagnosis of environmental concerns. The PCT analysis did not disclose information pertaining to this factor for the same reasons mentioned above. Other resources (e.g., air traffic controllers procedures, knowledge of current weather conditions) would be necessary to infer abnormalities of this nature.

The EID interface was able to support the detection and diagnosis of environmental concerns. It did so by displaying the constraints of the work domain that incorporates meteorological/terrain information. In this case, pilots can then readily obtain information as to the reason why certain frequencies might not reach the desired destination and therefore autonomously decide to communicate through another radio channel. What is currently being done is the request by pilots to air traffic centers for the use of other radio frequencies allowing exchanges given the current conditions. This demonstrates that in fact the work domain is distributed and its different constraints levels are delegated to operators having different work functions. A display showing the entirety of the work domain to operators might then eliminate this step.

CONCLUSIONS

The research presented in this paper allowed to compare PCT and EID using the CH-146 Griffon control display unit as a vehicle. The study showed that PCT and EID both have strengths and weaknesses as demonstrated by this evaluation. The PCT interface did not aid in diagnosis although it led to intuitive procedures needing to be performed in normal situations. Operator's goals geared toward diagnostic activities would have to be incorporated in the PCT analysis for it to support such eventualities.

The EID interface on the other hand allowed for normal exchanges to take place, detection of faults, and diagnosis of problems of environmental nature. However, an activity analysis would be necessary to delineate information which is pertinent for specific tasks.

Moreover, empirical evaluations would be necessary in order to evaluate the interface form – issues of information understandability and compatibility.

In all, it would seem beneficial to integrate the frameworks since they both bring their own distinctive set of design requirements necessary for effective performance in human-machine systems.

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