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Making the constraints visible: testing the ecological approach to interface design

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A haemodynamic monitoring and control task was used to evaluate the ecological approach to interface design for complex high-technology environments. Guidelines proposed by Bennett and Flach (1992) were used to design multilevel displays that made visible (a) anatomical constraints, and (b) causal constraints on haemodynamic systems. These displays were compared with a traditional display that showed pressure and flow values in five separate graphs. Simulations of clinical problems were generated by a computer model and presented in an interactive computer environment. Critical care nurses and nursing students observed changes in pressures and flow corresponding to certain disease states and corrected those states using simulated drugs. For both groups, speed and accuracy were progressively improved by the enhanced, multilevel displays.

1. Introduction

Complex, high-technology environments (nuclear power plants and air traffic control centres, for example) are qualitatively different from traditional work environments (e.g. assembly lines or switchboards) and therefore they make markedly different demands on their human operators (Vicente and Rasmussen 1990). Complex systems typically are composed of many highly coupled sub-systems. Consequently, not only are fault detection and correction more difficult, but also the tiniest error can cascade to produce potentially catastrophic consequences. Moreover, because complex dynamic systems tend to have long time constants that delay the system's response to a control action and because the performance of many automated controllers must be monitored simultaneously, operators' detection and control burdens can be overwhelming.

Complex high technologies also make very different demands on interface designers than traditional environments do. Current displays function largely as what Goodstein (1981) called 'single-sensor–single-indicator' devices. That is, for each device used, only a single variable is recorded. From the data generated from independent sensors, operators must select and integrate those data elements that are relevant to the immediate situation. The challenge for designers is to find ways to (a) maximize the benefits of technology that can record and present vast arrays of highly detailed data, and (b) minimize the stress on the operators who must integrate all that data into useful information. For the designer, this means constraining the degrees of freedom in the display by determining not only which of the many sub-systems to represent in the interface, but also how to represent the relationships among those sub-systems.

The goal of the current research was to explore specific interface design strategies for constraining the degrees of freedom to see if they do indeed improve operator performance in monitoring and controlling complex high-technology systems. This was done in a particular environment—Intensive Care Unit monitoring—that epitomizes the challenges to designers and operators alike. The premise is that degrees of freedom will be reduced, and operator performance improved, by making relevant sub-system links visible in the display.

1.1. *The ecological approach to interface design*

The ecological perspective on interface design is derived from an approach to psychology advanced by J. J. Gibson (1966, [1979] 1986). In contrast to the traditional (and predominant) view of psychology as the study of the human organism (what Vicente (1995) calls the organismic approach), the ecological approach views psychology as the study of the interaction between an organism and its environment (Gibson 1966, [1979] 1986, Michaels and Carello 1981). When applied to human factors and ergonomics, this view suggests that because the human operator and the work environment are reciprocally coupled, they cannot be studied independently of each other (Vicente 1992a, 1995, Vicente and Rasmussen 1990, 1992). Meister (1989) has made a similar distinction between the ecological and organismic approaches, describing them as systems and psychological perspectives, respectively. The similarity of the ecological view to systems theory also was acknowledged by Gibson ([1979] 1986).

Ecological interface design should begin by identifying the constraints in the environment (i.e. the work domain) that are relevant to the operator and to system goals (Rasmussen 1986, Vicente 1995, Woods and Roth 1989). This emphasis on learning how environmental constraints can support skilled behaviour contrasts sharply with the organismic approach, which tends to minimize contextual or environmental influences, instead ascribing skilled behaviour to elaborate mental constructs and cognitive processes (Vicente 1995, Kirlik 1995). However, there is evidence to suggest that when a careful, goal-relevant analysis of the task environment is conducted, a more parsimonious description of human performance is possible (Boer and Kugler 1977, Kirlik *et al.* 1993, Vicente 1995).

The emphasis placed by the ecological approach on environmental analysis can be seen in its approach to task analysis. Traditional, operator-focused task analysis methods frequently result in descriptions characterized as single, temporal sequences of overt behaviours (Meister 1985). These descriptions have proved to be inadequate for complex work domains where variability can be due to: (a) variations in the state of the system when an intervention is initiated, (b) the unpredictability of external disturbances in open systems, or (c) operator characteristics such as skill level or strategy preferences (cf. Rasmussen 1986). To incorporate these different sources of variability, the ecological approach employs separate descriptions of the functional problem space, task goals, and operator characteristics, assuming that observed behaviour will be a function of the interaction of these three sources of constraints (Vicente 1995).

The goal of ecological interface design is to make the identified work domain constraints visible in the interface. Making the constraints visible (rather than remembered) is not, in and of itself, so unusual, as is determining which kinds of constraints to make visible. Information can be characterized as lying along a continuum of higher-order variables (or high-level constraints) such as process

status or relationships between variables to low-level data such as the values of individual variables (Bennett *et al.* 1993). The traditional (organismic) approach has favoured using low-level environmental variables (or constraints) and relying on the organism to integrate these into higher-order information. This has led to the promulgation of single-sensor–single-indicator (SSSI) interface designs that place most of the burden for data integration on the operator.

In contrast, ecological psychology claims that an individual's primary source of environmental information to support goal-directed activity is more likely to be complex, higher-order variables specifically related to the goal than the lower-order variables commonly described by physics (Gibson 1966, [1979] 1986, Michaels and Carello 1981, Runeson 1977). The prominence of higher-order information is evident as well in research on object (or configural) display designs (Carswell and Wickens 1987, Casey and Wickens 1986, Chernoff 1973, Sanderson *et al.* 1989) with emergent features (Barnett and Wickens 1988, Garner 1981, Pomerantz 1986). Sanderson and colleagues (Sanderson *et al.* 1989) have claimed that what some have called 'emergent features' can be characterized more accurately as what ecological psychology has termed invariants (following its usage in mathematics), that is, as physical properties of an object or system that remain unchanged under a range of transformations (Gibson 1979 [1986], Michaels and Carello 1981, Warren and Shaw 1985).

Flach (1990) has asserted that designing computer interfaces for complex, high technology environments requires the designer to carry out 'inverse ecological physics'. In ecological physics (Gibson 1966, [1979] 1986), the scientist's challenge is to describe the information nature has made available in the medium that allows perception of the corresponding environmental properties. For example, researchers in visual perception may describe the available information as complex patternings in the light (the medium) as it reflects off the particular surfaces and substances in ways that specify a sunny day, a chair, or an old friend. In contrast, designers of interfaces for complex domains have no natural source, or medium, for information (e.g. as provided by an optic or acoustic array); instead, they must construct an information source from a variety of perspectives or observables provided by available measurement devices. Using 'inverse ecological physics', designers must engineer the invariants presented in the display medium by identifying the intrinsic constraints of the targeted work domain and then must map those constraints onto the geometry of the interface. Because the constraints in complex systems exist at many levels (e.g. goals, structure, components), designers have begun to recognize the need to map multiple levels of constraint onto the interface geometry of complex systems (c.f. Beltracchi's 1987 Rankine Cycle Display, Westinghouse's ACR Displays [Carrera *et al.* 1991, Eastman *et al.* 1986, Woods and Eastman 1989], and Vicente and Rasmussen's 1990, 1992 Ecological Interface Design [Vicente 1992a, b]).

Bennett and Flach (1992) have offered three guidelines by which this kind of semantic mapping might be applied to graphic design: (a) represent each relevant process variable with a distinct element in the display, (b) organize display elements so symmetries that arise from their interaction correspond to higher-order constraints in the process, and (c) nest the symmetries of the display in ways that reflect the hierarchical structure of the process. Taken alone, Bennett and Flach's first guideline corresponds closely to the elemental, organismic (SSSI) design approach. From the ecological point of view, describing the relevant process variables is surely necessary. Indeed, identifying the relevant variables to display is rarely trivial. However, although necessary to the ecological approach, displaying the relevant variables is

not sufficient by itself unless integrated higher-order structural and functional system constraints are also described (cf. Vicente and Rasmussen 1990). The present research applies ecological principles to the design of displays in a specific complex, high-technology domain (intensive care) and, at the same time, provides an initial empirical test of the proposed semantic mapping guidelines of Bennett and Flach (1992).

1.2. *Haemodynamic monitoring in Intensive Care Units*

Because of the proliferation of sophisticated physiological monitoring devices, today's intensive care units share all the characteristics of complex, high-technology environments. The new monitoring technology has been beneficial in many ways, for example, enabling clinicians to obtain rapid, frequent, repeated measures of physiologic parameters in order to detect potential problems sufficiently early to institute appropriate therapy. However, the technological innovations have also produced new problems (Sinclair 1988). Most monitoring devices still function essentially as 'single-sensor–single-indicator' devices (Goodstein 1981). From the vast array of data elements, clinicians must select and integrate those most relevant to the immediate situation.

Attempts by designers of physiological monitoring devices and critical care patient care information systems to 'integrate' data are rudimentary at best and remain essentially unchanged from the situation described by Galer and Yap (1980). Although clinicians can now graph or trend values for some parameters over time, the task of integrating discrete (or trended) data for as many as 60 parameters into diagnostic information remains the responsibility of the clinician.

It is not enough for clinicians to determine solely which indicators identify a problem. Minimally, the clinician must arrive at a 'diagnosis' (problem definition), an 'etiology' (cause or causes), and a 'prognosis' (likely outcome with and without treatment) for the patient before deciding whether to apply treatment or to let nature run its course. Reciprocally, from a number of possible modes of treatment, clinicians must select an appropriate treatment and apply it in the right dosage and frequency to correct the identified problem—without creating a new problem or intensifying a problem in another sub-system. As a result, clinicians have, not only the single-sensor–single-indicator problem of Goodstein (1981), but also a reciprocal 'single-effector–single-controller' problem (see Turvey *et al.* 1978, for a detailed description of this problem in other contexts). (An analogous problem is encountered in studies of movement. Without some higher-order control mechanism to co-ordinate the very many degrees of freedom represented in the muscles and joints of the musculoskeletal system as discrete effectors, co-ordinated movement would be impossible. Here, co-ordination of treatment is made more difficult because there are no higher-order control mechanisms by which to co-ordinate the degrees of freedom represented by the six discrete drugs. Each drug must be controlled independently.) The clinical co-ordination problem, then, can be understood as a complex physical system that has dual patient (diagnosis) and clinician (treatment) sub-systems.

Take, for example, one subset of intensive care unit concerns, haemodynamic monitoring and control. To carry out haemodynamic monitoring adequately, clinicians must learn not just discrete values of pressures and flow (figure 1a), but three sets of relationships within the patient sub-system. The first is the relationship between the values of pressures and flows at various points in the circulatory system (heart, arteries, and veins, for example) (Sinclair 1988). Understanding this relationship (figure 1b) leads the clinician to a diagnosis of the patient's problem

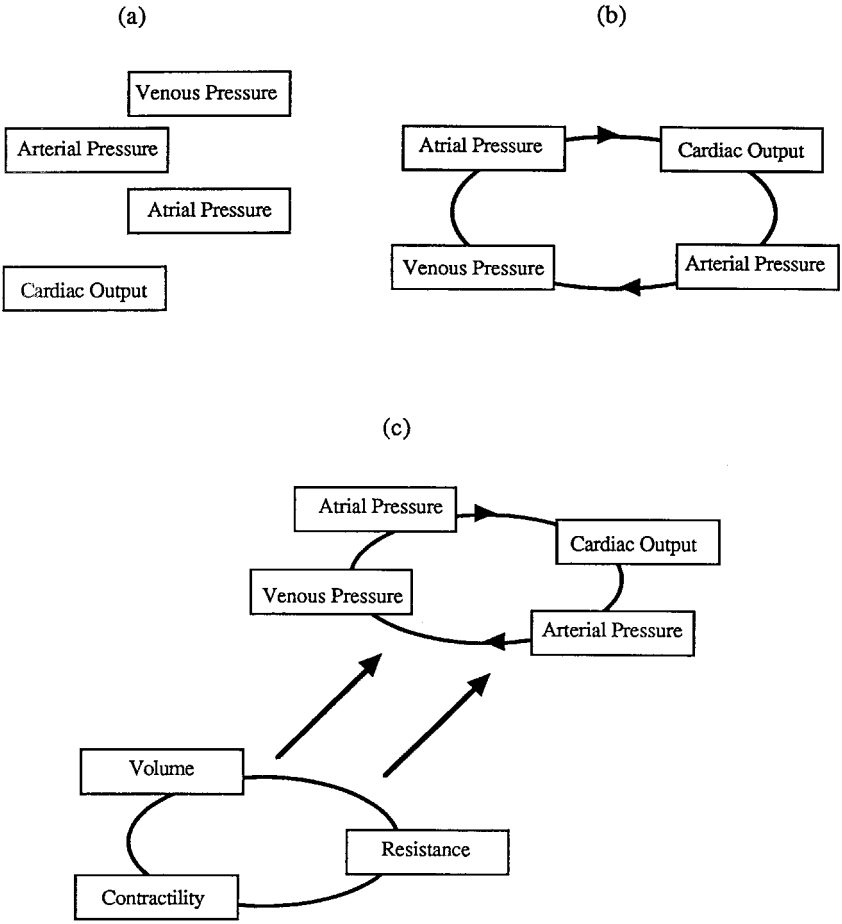

Figure 1. Three views of the haemodynamic system (as represented in the Guyton model): (a) pressure and flow observables shown as independent entities; (b) observables shown with their anatomic constraints; and (c) observables shown linked to their aetiological (causal) constraints.

('what' is wrong). The second is the relationship between underlying causal factors and the pressures and flows (figure 1c). Significantly, pressure at each point in the system is determined by flow and resistance; flow is determined by volume, heart strength (and heart rate) and resistance (Guyton 1980). The haemodynamic problem described here has much in common with process control problems in other domains (cf. the description of the physical structure of DURESS, a simulated thermal-hydraulic process by Vicente and Rasmussen 1990, 1992). Understanding these relationships allows the clinician to understand the etiology (cause or causes) of the patient's problem. Therapy is directed at etiological factors whenever possible, therefore this provides the answer to the 'how' to correct question.

As is true in many complex dynamic systems, there are rarely, if ever, one-to-one relationships in haemodynamics. Instead, the mappings tend to be one to many, many to one, or many to many. For example, a change in arterial pressure may be due to increased fluid volume, increased resistance between arteries and veins, or increased heart strength (or contractility). Unless the specific cause for the increased pressure is

known, the clinician must direct therapy at each of these possible sources in turn. Determining a third relationship, the patient's potential capacity for healing, the disease state's potential capacity for further injury or insult to the system, and the availability of treatment—given an overarching goal of returning the patient to as healthy state as possible—determines a prognosis, or probable outcome, with and without treatment. Understanding this relationship answers the 'why' and 'why not' of treatment.

1.3. *Applying ecological design principles to haemodynamic displays*

To assess the effectiveness of the proposed display design guidelines, the authors implemented Guyton's (1980) model of haemodynamics (see Effken (1993) for the rationale). In Guyton's model, which shows how the basic components of the circulation relate to arterial pressure control, the entire blood volume is contained in three capacitative reservoirs—the arteries, the veins, and the heart, each reservoir having its own pressure gradients, volume, and flow. The pumping heart generates flow that is impeded by the resistance in the arteries and the resistance in the veins. The effects of changing a given independent variable on the dependent variables of the model have been reported by Guyton (1980) and were used to validate the accuracy of the subsequent computer display (see the Appendix for the computer simulation).

The Guyton data provide a functional description of the haemodynamic problem space and were presented in three different visual formats that incrementally incorporate the guidelines of Bennett and Flach (1992): the traditional strip-chart display (e.g. figure 3) makes available relevant process variables as distinct display elements (guideline 1) and corresponds to figure 1a. The strip-chart display was adapted from a design used by Deneault *et al.* (1990) to compare the performance of anaesthesiologists with a traditional (the strip-chart) and an object display (see also Galer and Yap 1980). The strip-chart display can be seen as an example of the single-sensor–single-indicator device of Goodstein (1981). To identify the state of the system, the operator must rely on previous education and domain knowledge to integrate correctly the available raw data.

Bennett and Flach's second guideline moves beyond traditional interface design to require that the designer identify higher-order system constraints. This is a non-trivial task because, as noted previously, complex systems generally feature multiple levels of constraint and many-to-many mappings between levels. One way to approach the problem is to capitalize on the inherent physical connectivity in a system (cf. Reuleaux [1876] 1963, Turvey *et al.* 1978, Vicente and Rasmussen 1990, 1992). The integrated balloon display (e.g. figures 4 and 5) structures the display elements by embedding them within the context of underlying anatomical constraints (per guideline 2) and corresponds to figure 1b. The major constraints shown describe the structural relationships, or connectivity, of the system. Arteries, veins, and heart are not independent, but physically connected. The authors hypothesized that, if these constraints were made visible, observers would learn to anticipate the effect of a change in one component area, for example, a drop in right atrial pressure, on a subsequent change in another component area, for example, cardiac output.

Bennett and Flach's third guideline dictates nesting the display in ways that make clear the hierarchical structure of the process. The etiological potentials display (e.g. figures 6 and 7) makes visible the relationship of etiological factors to symptoms (the functional relationships) by showing how the underlying control parameters (heart strength, volume and resistance) relate to the overall target state of the system and to

each pressure and flow (per guideline 3) and corresponds to figure 1c. These levels of constraint correspond (at least in their general descriptive terms) to levels in the abstraction hierarchy of Rasmussen (1985, 1986) as described by Vicente and Rasmussen (1990, 1992) and used to develop their Ecological Display Design for DURESS.

The first two displays attempt to enhance the clinician's diagnostic capabilities. That is, they make relevant information about the patient's symptoms (blood pressure and flow) available to the clinician. In the first, symptoms are displayed as discrete values. In the second, symptoms are shown as they relate to each other physically. The third design attempts to enhance both the clinician's perception and action by making visible how etiological factors relate to the patient's symptoms, that is, abnormalities in pressure and flow (figure 1c). However, because these causal constraints have a one-to-one mapping with the control parameters (drugs), the relationship of treatment to diagnosis is made transparent in the display. (For the purposes of these studies, generic drug categories were used that acted in a 1:1 manner on the control parameters of the Guyton model. In the actual clinical setting, this would not be true, except in very unusual circumstances. It is more commonly the case that drugs affect several components to varying degrees.). It was expected that, not only diagnosis, but also treatment, would be enhanced because patient information is presented at the precise level required for clinician control.

1.4. *Comparing the haemodynamic displays*

Each display makes visible different kinds of constraints, therefore it was expected that the displays would have predictable, but differential, effects on problem detection and control. A summary of these predictions is presented in table 1. Moreover, given that the displays are differentially integrated, their effectiveness should vary as a function of the different integration requirements of the scenarios. Finally, differences should be modulated (i.e. constrained) by the skill level of the user (see below).

Given the ongoing, cyclical nature of diagnosis and treatment in intensive care, it is difficult to isolate discrete measures of detection and control. None the less, for the purposes of this research, detection was operationalized in terms of time to initiate treatment; and control was operationalized as number of drugs used. A third measure, percentage of time within target range, was assumed to incorporate both diagnosis and treatment (i.e. detection and control) components.

The authors expected that showing how pressure and flow are constrained by their anatomical connections in the integrated balloon display (IBD) would facilitate problem detection by observers that would be evidenced as earlier treatment initiation. In the etiological display (EPD), these relationships are shown in a more

Table 1. Predicted display type ordering for the four dependent variables used to assess diagnosis and control by novices and experts.

	Skill level	
Dependent variable	Expert	Novice
Time to initiate treatment	TSD > IBD > EPD	TSD > IBD > EPD
Number of drugs	TSD = IBD > EPD	TSD = IBD > EPD
% time in range	TSD = IBD < EPD	TSD < IBD < EPD

TSD, strip-chart display; IBD, balloon display; EPD, etiological display.

abstract fashion (as changes in the size and shape of a four-sided object). In this display, however, it was expected that problem detection would be facilitated by the fact that the normal, targeted state is highly symmetrical, making deviations from that state easy to detect. Consequently, still further improvement in treatment initiation time with the etiological display (EPD) was expected.

Neither the strip-chart display (TSD) nor the balloon display (IBD) enhance information for drug control. Only the etiological display (EPD) provides information on how the underlying causal, or etiological, factors (at which drug control is directed) relate to pressure and flow. Consequently, it was expected that only the etiological display (EPD) would decrease the number of drugs used by participants.

The authors assumed that the third measure, percentage of time in target range, incorporates both diagnosis and treatment components, and therefore it was expected that the effects of the display on that performance measure would be affected by enhanced information for both fault detection and control in the displays. Both the balloon display and the etiological display are presumed to enhance diagnosis, but the etiological display also is assumed to enhance treatment, and therefore it was expected that the highest percentage of time in target range would be achieved when using EPD, followed by IBD and TSD, in that order.

Considerable empirical evidence exists supporting the advantages of configural displays over separate displays for tasks that require data integration (Bennett *et al.* 1993; and see Bennett and Flach (1992) for a more comprehensive review). Based on this, it was expected that the effects on performance of the non-integrated TSD and the integrated IBD and EPD would be affected differentially by the integration requirements of scenarios. High resistance and low heart strength scenarios are created by changing only one parameter in the Guyton equations (resistance or heart strength, respectively). Ultimately, a change in one parameter will increase or decrease values of all three pressures and cardiac output; but there is, in some cases, an initial more localized effect (in the case of heart strength, on cardiac output or flow through the ventricle; in the case of resistance, on the resistance indicator). Low fluid, in contrast, is generated by changing three parameters in the Guyton equations and results in a decrease of all pressures and flow, although at different rates. Since the resultant effect is more global—hence, more integrated—in nature, it was expected that the low fluid scenario would prove more amenable to diagnosis and treatment with the more integrated displays, IBD and EPD.

Based on the literature on expertise, it was expected that experts would take longer than novices to begin treatment, but then would demonstrate highly efficient drug control. Experts in various fields such as physics, mathematics, and economics have been shown to take time to understand (i.e. to analyse qualitatively) the problem and plan their approach before initiating actions. Novices, in contrast, typically take little time to plan before they act, often using rapid-fire, trial and error control strategies (Glaser and Chi 1988, Larkin 1983, Paige and Simon 1966, Voss and Post 1988). Further, it was expected that experts would show a high degree of accuracy when using each display and, therefore, have little room to improve with informationally-enhanced displays because of their clinical knowledge and the simplicity of the clinical scenarios used. In addition, it was expected that the integrated balloon display (IBD) would provide novices with the anatomical information support they needed to achieve the level of performance that experts achieved with the anatomically unenhanced strip-chart display (TSD). Finally,

because of their knowledge of the kinds of drugs shown in the experiment, it was expected that experts would use fewer drugs to correct problems than novices.

Experiment 1 uses a between-subjects design to compare the effects of the three display designs on treatment co-ordination by novices. This design has the strength of avoiding asymmetrical transfer, but does not allow for operators to provide feedback about the comparative utility of each display. Experiment 2 seeks to remedy that problem by comparing the three displays in a within-subjects design. Experiments 1 and 2 were conducted using non-clinical participants, but that is not really the target population for these displays. Consequently, Experiment 3 compares the performance of novice and expert clinicians with the three displays.

2. Experiment 1

2.1. *Method*

2.1.1. *Participants*: Nineteen psychology undergraduates at the University of Connecticut (10 females and 9 males) participated as one way of partially fulfilling a course requirement. All participants had normal or corrected-to-normal vision and normal colour vision. A stratified quota sampling technique was used to assign equal numbers of men and women to each display type condition. One male participant using the balloon display did not complete the practice phase of the experiment within the allotted time, so data for 18 participants (10 females and 8 males) were analysed.

2.1.2. *Apparatus*: The dynamic simulations were developed and presented on a Sun 4/260 workstation equipped with a 19 in. colour monitor and SunView graphics tools. Participants observed changes in pressure and flow that corresponded to certain disease states and corrected those states using simulated drugs. A double buffering technique was used to smooth the animation so that the normal 1-s screen refresh (update) rate would be minimally detectable.

2.1.3. *Displays*: Data from Guyton's (1980) simulation of a basic haemodynamic model were presented in three different visual formats: a traditional strip-chart display, an integrated balloon display, and an etiological potentials display. Drug controls are the same for all displays. The six 'drugs' that participants use to treat observed haemodynamic problems are shown in a separate window (figure 2). Drugs act directly on the etiological factors of resistance, heart strength, and volume. To facilitate both learning and analysis, no drug affected more than one parameter. Generic dose categories (high, medium, low) were used. Participants selected a desired dose and drug, then pressed a mouse button to give discrete 'drug' doses. Clinical consultants had no trouble with using these simplified therapy options.

2.1.4. *The traditional strip-chart display (TSD)*: In the traditional strip-chart display, arterial, venous, and atrial pressure, cardiac output, and resistance are plotted as five separate bar graphs 100 pixels high and 300 pixels long (figure 3). The terms used to label the displays differ somewhat from those used in critical care settings. For example, 'resistance' as used in the displays is a more generic term than the 'systematic vascular resistance' (SVR) with which critical care clinicians work. The more generic, physiological labels were used because the authors wanted to investigate the utility of the displays for students with no clinical experience, as well as for highly experienced critical care clinicians. The instructions given to participants helped experienced clinicians to relate the generic terms to the specific terms encountered in their practice.

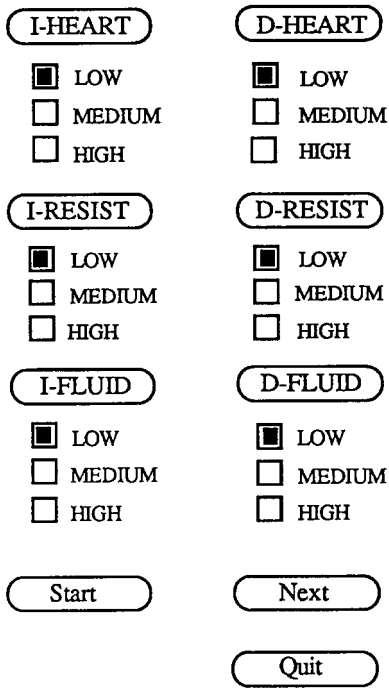

Figure 2. The drug control window.

Values for each parameter are selected by sampling the Guyton simulation at 1-s intervals.

The computer records the amount and strength of each drug used and the number of key presses made. Participant responses are also recorded as a time series (collected at 1-s intervals) of the values of the three pressures and cardiac flow, heart strength, resistances, and unstressed volume.

2.1.5. *The integrated balloon display (IBD)*: The integrated balloon display is probably best described as an animated mimic diagram. The diagram was adapted from a figure used by Guyton (1980) to describe the relationships of major components in the haemodynamic system. In the integrated balloon display, arterial, venous, and right atrial pressures are shown as changes in the horizontal dimension of three ellipses (balloons) (figures 4 and 5). The 'balloon' imagery was chosen deliberately as a kinematic analogue for the underlying dynamics of blood vessels, which have many of the same characteristics as balloons (Crane 1973, Weinhaus and Barker 1978). Both balloons and small blood vessels are characterized by curved elastic membranes, therefore they share the same basic force relationships that can be used to explain observed characteristics of blood flow systems. Specifically, the variable tension force in an elastic membrane produces an *N*-shaped pressure curve as volume is increased. In future enhancements of this particular display, it is hoped to make visible the underlying components of pressure (as they occur in both balloons and blood vessels). This would mean making visible the specific pressure, volume, and compliance (primarily wall thickness) measures for each compartment. Restrictions imposed by current graphics software have prevented the authors from showing that level of detail to date. The left ventricle is shown as an accordion-like (bellows) icon to capture pictorially the heart's

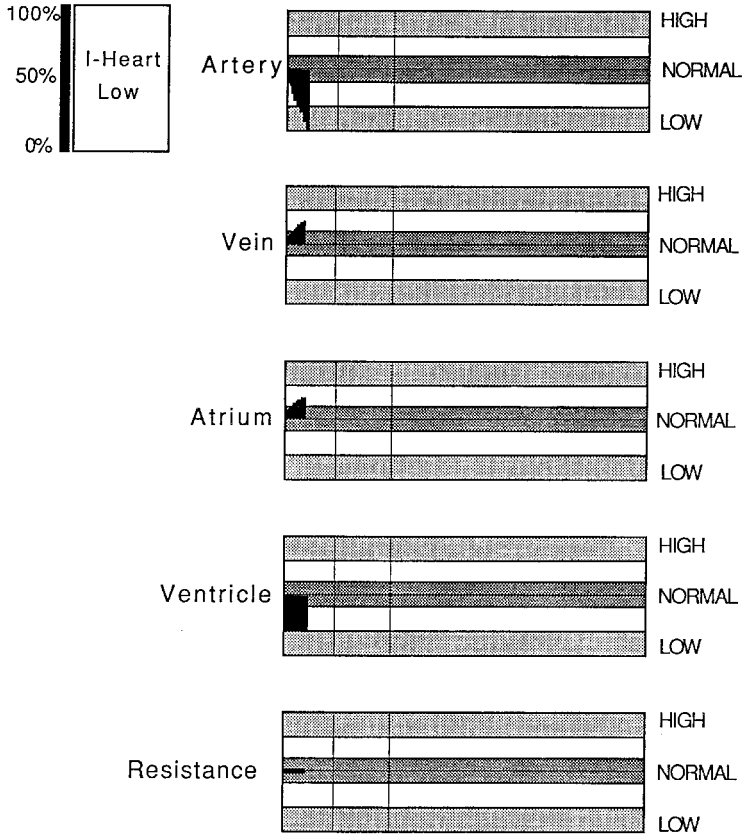

Figure 3. The traditional strip-chart display (TSD) in the low heart strength state. The vertical axis is colour coded for target range (green) and danger regions (red). The system is initiated with all variables in the normal condition, and bars generated each second show how the system gradually moves out of the target range. Arterial pressure drops, venous and atrial pressure increase, and the cardiac output (ventricle) is consistently low. When participants correct the problem, all variables will lie within the targeted 'normal' region shown by the central bar in each graph. When participants select a drug and a dose, the name of the drug and the dose are displayed on the 'bottle' at the upper left. A vertical bar graph on the outside of the drug bottle icon indicates the amount of drug still available to be given by the clinician. Although one has the capability to restrict the amount of each drug that a participant can use during a given trial, in the experiments reported here, the amount of drug available was not restricted.

forcing function on blood flow. A modified bar graph is superimposed over the balloons and bellows to show target (green) and high and low danger (red) regions. The capillary bed and kidney are shown as ellipses, but are static.

Each compartment (balloon or bellows) is connected to the next by two parallel lines 10 pixels in width. The connectors between the arteries and capillary bed and between the veins and right atrium indicate changes in resistance to flow by a change in the diameter of the distal end of the connection. With maximal resistance to flow, the connection closes; with minimal resistance values, the width increases to approximately 20 pixels. The intent was to depict resistance kinematically as a 'funnel' that impedes or facilitates blood flow. The optimal state is nearly, but not quite, parallel.

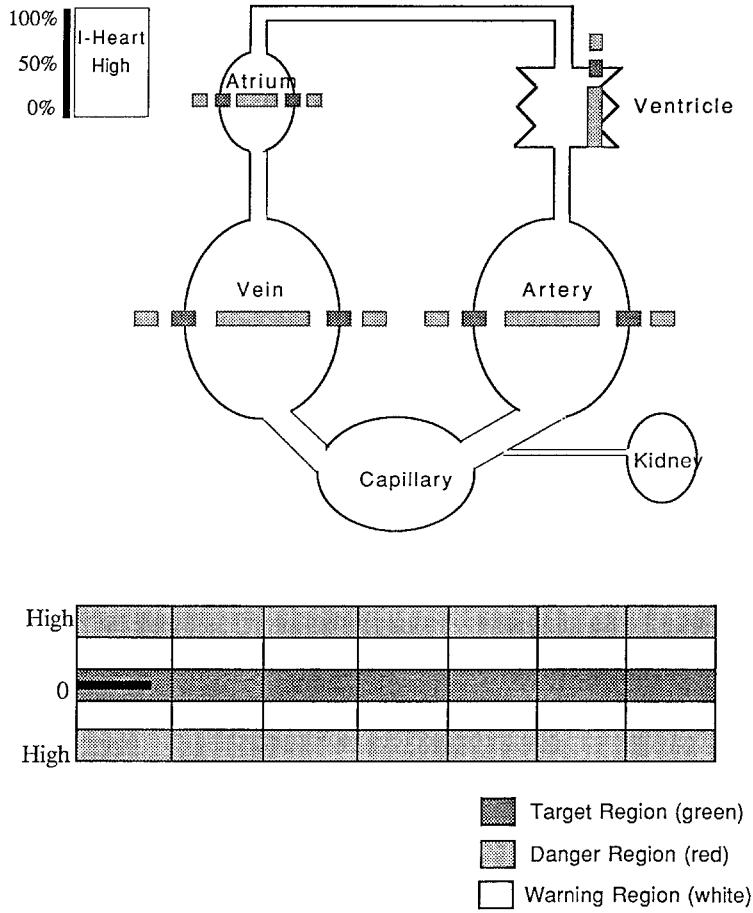

Figure 4. The integrated balloon display (IBD) in the targeted 'normal' state. In various 'disease' states, the horizontal dimension of arterial and venous ellipses can change from a maximum of 200 pixels in diameter to a minimum of 100 pixels, while the vertical dimension remains stationary at 200 pixels. The smaller atrium changes in diameter from 50–100 pixels when going from minimum to maximum pressure. The vertical dimension of the ventricle ranges from 40–80 pixels to indicate corresponding changes in cardiac output. The lower part of the main window contains a bar graph showing overall system status (calculated as the mean of the standardized, absolute distances from normal for the four dependent variables). The 55 × 660 pixel bar graph is a reflected graph in which the zero point (optimal value) is at the centre of the vertical dimension and the end points are both labelled as high (that is, far from normal). Bars 1 pixel wide are generated at 1 s intervals, but displayed at 10 s intervals. In the target (goal) state, the lateral walls of each of the ellipses that indicate pressure and the top of the bellows indicating cardiac output lie within the green target range shown by the bar graph over each, and the bar graph showing the overall state of the system lies within the green target range as well.

2.1.6. *The etiological potentials display (EPD)*: In the etiological potentials display, arterial, venous, and atrial pressures, and cardiac output are shown as vertices of a four-sided figure (figures 6 and 7). The ranges of values that pressures and flow might assume have been normalized so that, when values are normal, the figure approximates a (1·3 × 1·3 cm) square and is positioned in the centre of the screen. The square can move in a two-dimensional (etiological) space defined by horizontal and vertical

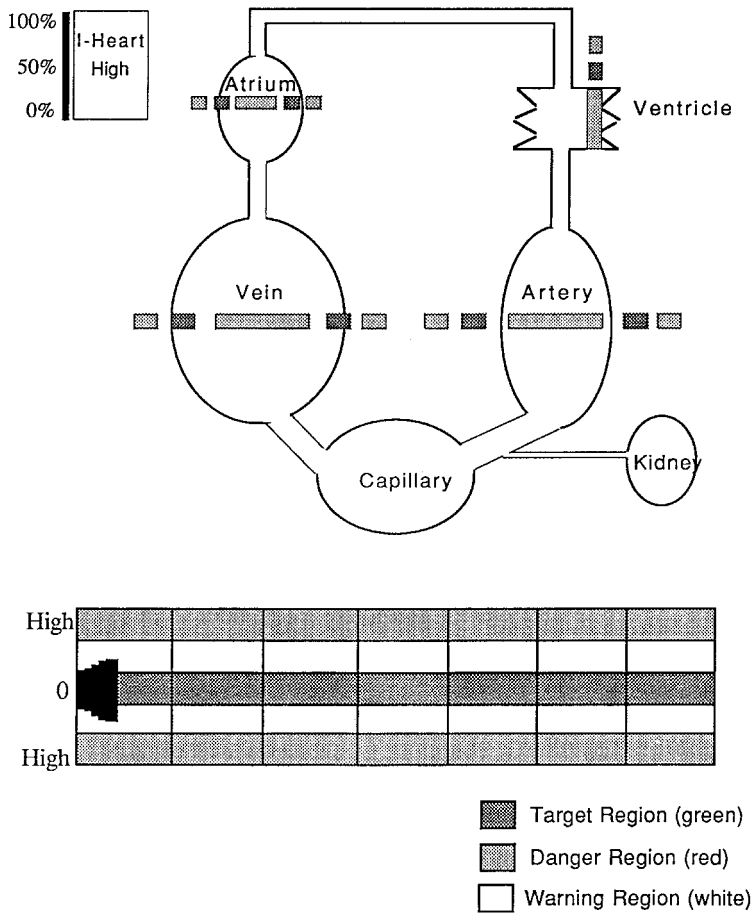

Figure 5. The integrated balloon display (IBD) in the low heart strength state. In the low heart strength state, the artery balloon shrinks so that its lateral walls approach the red danger region, while the vein and atrium balloons (venous and atrial pressure) increase in size to a point where the lateral wall of the balloon moves to lie in the high 'warning' range. Simultaneously, cardiac output (shown by the ventricle 'bellows') decreases so that the top of the bellows lies at the top of the red 'danger' region.

bars that cross at the centre of the screen (window). Fluid changes in the patient system are shown as an 'expanding' or 'shrinking' square. With changing pressures and flow, the 'square' moves along one or more of the axes and deforms.

2.1.7. *The scenarios*: Test scenarios were developed in conjunction with clinical experts to depict problems commonly seen in intensive care (high blood pressure, heart failure, and hypovolemia, for example). Simulated physiological data were used because, in actual patient data, underlying physiological trends are confounded with clinical interventions (Deneault *et al.* 1990).

To create a scenario ('illness'), the experimenter changes the value of any or all of the control parameters in the Guyton equations. In the experiments reported here, three parameters (resistance, heart strength, and unstressed fluid volume) were changed to create 'illnesses' such as hypertension, heart failure, or hypovolemia, respectively.

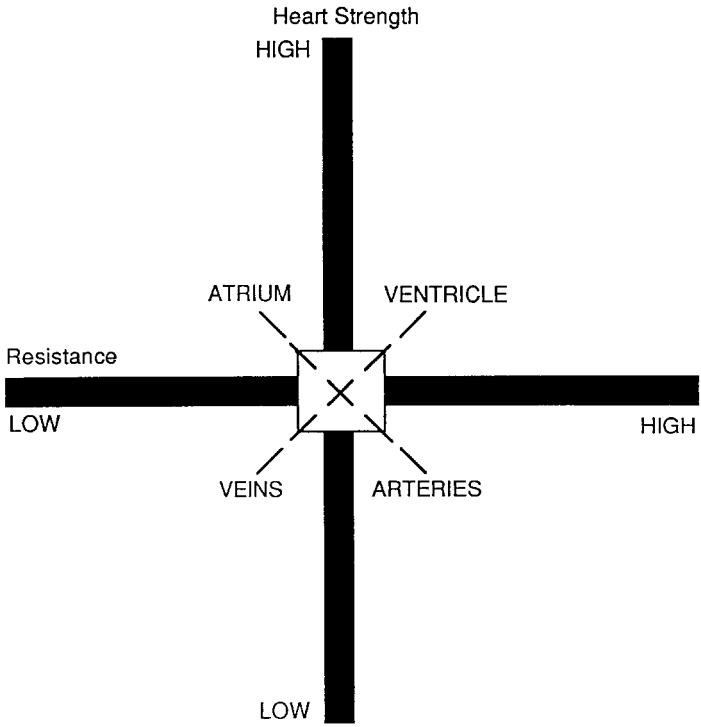

Figure 6. The etiological potentials display (EPD) in the normal (goal) state. Values for the three pressures and flow are shown as the vertices of a four-sided object that moves through a two-dimensional space in which the vertical axis represents heart strength and the horizontal axis represents resistance. Fluid changes are shown as a shrinking or expanding 'square'. The bars representing heart strength and resistance are 20 pixels wide by 650 pixels long. The central crossing point for each bar (axis) represents the optimal value for each. The amount of resistance and heart strength drugs available to be given by the clinician is shown by a red bar within the resistance and heart strength axis, respectively, that originates at the crossing point and gradually diminishes in size as a particular drug is used. Narrow (2 pixels wide, 230 pixels long) diagonal bar graphs indicate target and danger ranges for pressures and flow. Target regions are green; danger regions are red.

Four output variables in the Guyton equations, recognized by clinical experts as critical determinants of haemodynamic status that typically require treatment (arterial pressure, venous pressure, right atrial pressure, and cardiac output), are explicitly shown in the display. In addition, one input variable in the Guyton equations—resistance—is shown, because that value also is used frequently in diagnosis and treatment.

2.1.8. *Design and procedure*: Three display types (traditional strip-chart, integrated balloon display, and etiological potentials display) were between-subjects variables and three scenarios (low heart strength, high resistance, and low fluid) were within-subjects variables in the mixed design. Participants were shown the scenarios depicting common clinical problems (e.g. heart attack, high blood pressure, or bleeding) and were asked to treat observed 'illnesses' using the simulated 'drugs'. Participants were not asked to label the problems they observed; nor were they told in

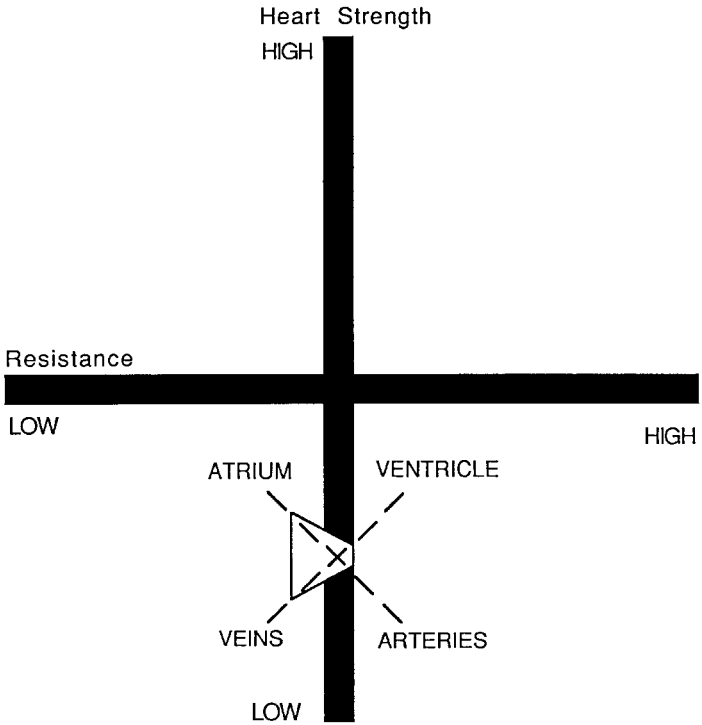

Figure 7. The etiological potentials display (EPD) showing the same low heart strength state as in figures 3 and 5. As the values of pressure and flow move away from the targeted state, the four-sided object deforms and moves away from the central crossing point of the resistance and heart strength axes.

advance the kinds of problems they would be shown. Participants were asked to get their 'patients' into the normal range for all three pressures and cardiac output as quickly as possible.

Participants were given a 20–30 minute training session. The session included reading written instructions that explained the purpose of the experiment, gave a brief description of haemodynamics, then explained the particular display the participant would use. The experimenter demonstrated the changes that participants might see the model undergo with the display. Participants then practiced using the drugs on the display (in a normal state) until comfortable with their use.

In practice trials, participants experienced the three scenarios that would be seen in the test condition, but at different absolute values. Participants were required to solve each scenario twice before being allowed to continue on to the main experiment. In the test situation, each scenario was presented twice for a total of six trials. Each scenario lasted for a maximum of 2 min, but participants could terminate trials whenever they had corrected a problem to their satisfaction by pressing a 'NEXT' button. The presentation order of scenarios was randomized. Participants were tested individually.

2.2. *Results*

A summary of the results of experiment 1 is shown in table 2. As expected, participants using EPD outperformed participants using other displays on all

Table 2. The effect of display type on performance for the 18 participants in experiment 1.

	Display type		
Performance measure	TSD	IBD	EPD
Time to initiate treatment (s)	8·1	7·4	6·1
Number of drugs**	3·3	3·4	1·6
% time in range***	54·0	43·0	89·0

Display type was significant at the level indicated: **$p < 0.01$; ***$p < 0.001$.

measures. The effect of trials was not significant, and therefore unless specified, data have been summarized over trials.

2.2.1. *Time to initiate treatment*: Time to initiate treatment is defined as the number of seconds from scenario onset to initial application of therapy. Display types were ordered as predicted, but a 3 (display type) ×3 (scenario) ANOVA revealed that display type was not a significant main effect, $F(2, 15) = 2.01$, $p > 0.10$.

2.2.2. *Number of drugs used*: A 3 (display type) ×3 (scenario) ANOVA revealed a significant main effect of display type, $F(2, 15) = 11.28$, $p = 0.001$. A *t*-test showed that both TSD and IBD differed significantly from EPD, $p < 0.01$, but not from each other.

2.2.3. *Percentage of time in target range*: Participants remained in the target range for a mean 65% of the time, but it varied from 0–94%. A 3 (display type) ×3 (scenario) ANOVA revealed a significant main effect of display type, $F(2, 15) = 19.36$, $p < 0.001$, and of scenario, $F(2, 30) = 3.33$, $p < 0.05$. Paired comparisons by *t*-tests showed that EPD differed significantly from TSD and from IBD, $p < 0.01$, but those two did not differ from each other. Likewise, low fluid ($M = 56\%$) differed from low heart strength ($M = 76\%$), $p < 0.05$, but not from high resistance ($M = 65\%$).

2.3. *Discussion*

With the exception of percentage of time in target range, displays were ordered as predicted. As expected, performance with EPD surpassed both IBD and TSD on all measures. Time to initiate treatment decreased approximately 1 s with each display enhancement. However, these differences were not statistically significant.

3. Experiment 2

In experiment 1, participants each used only one display type. As noted previously, this design has the strength of avoiding asymmetrical transfer from one display type to the other; but inter-subject variability makes it necessary to use many participants to detect significant differences between displays. In addition, only in a within-subjects design can participants make subjective comparisons of the three displays, and these data can be very useful. The objective of experiment 2 was to compare the performance of novice participants using all three displays and three scenarios in a within-subjects design.

3.1. *Method*

3.1.1. *Participants*: Thirteen psychology undergraduates (10 males and 3 females) at

Table 3. The effect of display type on performance for the 11 participants in experiment 2.

	Display type		
Performance measure	TSD	IBD	EPD
Time to initiate treatment (s)****	9·1	6·4	5·6
Number of drugs****	3·1	3·3	1·5
% time in range****	56·0	56·0	85·0

Display type was significant at the level indicated: ****$p < 0{\cdot}0001$.

the University of Connecticut participated in the experiment as one way to partially fulfill a course requirement. Of the thirteen, eleven (8 males and 3 females) completed the experiment. Two participants (both males) were not able to reach criterion in the practice phase within the allotted time of 1 h and were not allowed to continue to the test phase.

3.1.2. *Displays*: The same displays were used as in experiment 1.

3.1.3. *Design and procedure*: Display type and scenario were manipulated in the within-subjects design. The same scenarios (low fluid, low heart strength, and high resistance) were used as in experiment 1. The same procedure was followed as in experiment 1, except that participants practiced with each display. Presentation order for the displays was counterbalanced.

In the practice trials, participants were required to solve each scenario once with each display. Presentation order for the scenarios was counterbalanced; however, the same order was used for each display type.

3.2. *Results*

A summary of the results of experiment 2 is shown in table 3. Inspection of table 3 shows that display types ordered as predicted for time to initiate treatment and for number of drugs used. For percentage of time in target range, performance by participants using EPD surpassed TSD and IBD, but those two did not differ from each other. It was expected that the effects on performance using the three displays would be differentially affected by integration characteristics of the scenarios. This was shown to be the case.

3.2.1. *Time to initiate treatment*: Times to initiate treatment ranged from 2–23 s with a mean of 7·05 s. Means for the three display types are shown in table 3. A 3 (display type) ×3 (scenario) ANOVA revealed that these differences were significant, $F(2, 20) = 27{\cdot}50$, $p < 0{\cdot}0001$. A Tukey test showed that TSD differed significantly, $p < 0{\cdot}01$, from both IBD and EPD, but the latter two did not differ from each other.

The ANOVA showed that scenario means (low fluid = 7·62 s, high resistance = 7·06 s, and low heart strength = 6·42 s) were significantly different, $F(2, 20) = 4{\cdot}39$, $p < 0{\cdot}03$. A Tukey test revealed that low fluid differed significantly from low heart strength, $p < 0{\cdot}05$. The interaction of display type with scenario was not significant, $F(4, 40) = 1{\cdot}74$, $p > 0{\cdot}10$.

3.2.2. *Number of drugs used*: The number of drugs used by participants ranged from 1–6 (M = 2·62). A 3 (display type) ×3 (scenario) ANOVA revealed a significant main

effect of display type, $F(2, 20) = 29{\cdot}69$, $p < 0{\cdot}0001$. Paired comparisons by Tukey test showed that EPD differed significantly from both IBD and TSD, $p < 0{\cdot}01$, but that IBD and TSD did not differ significantly from each other.

Scenario means (low heart strength = 2·49, low fluid = 2·55, and high resistance = 2·85) were not a significant main effect in the ANOVA, $F < 1{\cdot}0$. However, the ANOVA revealed a significant interaction between display type and scenario, $F(4, 40) = 4{\cdot}80$, $p < 0{\cdot}01$. An analysis of the simple effects showed that display type was significant at low fluid, $F(2, 20) = 19{\cdot}40$, $p < 0{\cdot}001$, at low heart strength, $F(2, 20) = 12{\cdot}60$, $p < 0{\cdot}001$, and at high resistance, $F(2, 20) = 9{\cdot}34$, $p < 0{\cdot}001$. Specifically, when using EPD, participants required an average of 1 drug to solve the low fluid scenario, while requiring over 3 drugs with IBD or TSD. Similarly, participants using EPD required a mean of 1·7 drugs to correct high resistance problems, while using 3 drugs with IBD and 3·3 drugs with TSD. These findings are in conformity with the initial prediction that only EPD would support the use of fewer drugs. The low heart strength scenario showed the predicted effect of EPD as well. Participants used an average of 1·6 drugs to correct that problem with EPD, but used 2·1 drugs with TSD and 3·5 drugs with IBD. Discussion of possible reasons for the disparity between TSD and IBD in this scenario is reserved until later. In addition, the simple effects analysis showed that the effect of scenario was significant at TSD, $F(2, 20) = 3{\cdot}81$, $p < 0{\cdot}05$, and at EPD, $F(2, 20), = 8{\cdot}58$, $p < 0{\cdot}01$.

3.2.3. *Percentage of time in target range*: A 3 (display type) ×3 (scenario) ANOVA revealed a significant main effect of display type, $F(2, 20) = 31{\cdot}72$, $p < 0{\cdot}0001$, and a significant interaction between display type and scenario, $F(4, 40) = 8{\cdot}41$, $p < 0{\cdot}0001$. Solving the low fluid scenario was facilitated by each display type enhancement, as predicted. However, for low heart strength, the order of IBD and TSD was reversed: EPD > TSD > IBD, and for high resistance, EPD > IBD = TSD.

3.3. *Discussion*

As predicted, the etiological potentials display (EPD) improved performance in all categories measured. Moreover, solution speed improved dramatically with EPD. In addition, the number of drugs required to solve scenarios was again cut in half (as in experiment 1) with EPD.

4. Experiment 3

The target population for using these displays is critical care nurses, nurses preparing to enter critical care, and student nurses, therefore experiment 3 compared the performance of experienced critical care nurses and nursing students with the three display types. Experiment 3 also provided a way to test the hypothesis that skill level would modulate performance with the three displays.

4.1. *Method*

4.1.1. *Participants*: Nine experienced critical care nurses currently enrolled as graduate students at the University of Connecticut School of Nursing served as the 'expert' group. Critical care experience of the group ranged from 1–14 years with a mean of 6·2 years. The 'novice' group was composed of six senior nursing students at the University of Connecticut. Three experts failed to complete the experiment owing to external clinical time commitments; consequently, data for six experts and six novices were analysed. All participants had normal or corrected-to-normal vision and normal colour vision.

Table 4. Results of experiment 3 by skill level and display type for three performance measures.

	Skill level and display type					
	Expert (n = 6)			Novice (n = 6)		
Performance measure	TSD	IBD	EPD	TSD	IBD	EPD
Time to initiate treatment****	14·4	11·1	9·7	14·1	11·8	8·8
Number of drugs*	2·4	2·3	1·7	2·2	2·7	1·6
% time in range****	59·0	64·0	78·0	48·0	58·0	83·0

Display type was significant at the level indicated: *$p < 0{\cdot}05$; ****$p < 0{\cdot}0001$.

4.1.2. *Displays*: The same displays were used as in the previous experiments.

4.1.3. *Design and procedure*: Skill level (novice and expert) was a between-subjects variable; three display types (the traditional strip-chart, or TSD; the integrated balloon display, or IBD; and the etiological potentials display, or EPD) and three scenarios (low fluid, high resistance, and low heart strength) were within-subjects variables in the mixed design. The same procedure was followed as in experiment 2.

4.2. *Results and discussion*

The results are summarized in tables 4 and 5. Specific predictions had been made about the way displays would order for both detection and control (table 1). That predicted order held for each of the four dependent variables (table 4). Also as predicted, experts outperformed novices in terms of the percentage of time the system was maintained in target range when using TSD and IBD. As expected, the information provided by IBD allowed novices to achieve the performance experts achieved with TSD. EPD further enhanced the diagnosis and treatment performance of both groups. However, experts did not initiate treatment later than novices, nor did they use fewer drugs than novices, as had been anticipated. A more detailed analysis by dependent measure follows.

4.2.1. *Time to initiate treatment*: Time to initiate treatment ranged from 4–30 s. Means for the three display types were ordered as predicted: 9·25 s (EPD), 11·43 s (IBD), and 14·29 s (TSD). A 2 (skill level) ×3 (display type) ×3 (scenario) ×2 (trial) ANOVA revealed that this difference was significant, $F(2, 20) = 16{\cdot}82$, $p = 0{\cdot}0001$. Tukey multiple pairwise comparisons analysis showed that TSD differed significantly from both IBD and EPD, $p < 0{\cdot}01$, but that IBD and EPD did not differ significantly from each other.

In contrast to expectations, the ANOVA showed no difference between experts ($M = 11{\cdot}74$ s) and novices ($M = 11{\cdot}57$ s), ($F < 1{\cdot}0$). Both groups showed very similar patterns of improvement in treatment initiation time with IBD and EPD. Two things may have contributed to this result. First, in this experiment, participants were asked to correct the problems as quickly as possible; in the previous experiments involving novice and expert participants using IBD and TSD only (Effken 1993), the participants had been asked to correct the problem as quickly as they could while using as few drugs as possible (a more complex goal that requires optimizing accuracy *and* speed). In addition, the scenarios used in this experiment were simple (created by manipulating one independent variable in the Guyton equations). The previous experiments involving novices and experts had used both simple and complex

Table 5. Results of experiment 3 by display type, scenario, and skill level for three performance measures.

	Display type and scenario								
	TSD			IBD			EPD		
	LF	LHS	HR	LF	LHS	HR	LF	LHS	HR
Time to initiate treatment (s) ****									
Expert†	14·0	14·9	14·4	12·0	10·2	11·0	10·2	10·3	8·8
Novice‡	13·5	15·9	13·0	11·4	12·3	11·8	11·2	7·3	7·8
*Number of drugs**									
Expert†	1·8	2·8	2·6	1·8	2·5	2·4	1·2	1·9	2·0
Novice‡	2·6	2·9	1·7	1·5	3·5	3·0	2·0	1·3	1·6
Percentage of time in target range ****									
Expert†	66·0	57·0	54·0	76·0	68·0	47·0	83·0	77·0	72·0
Novice‡	33·0	50·0	59·0	78·0	41·0	56·0	78·0	88·0	84·0

Display type was significant at the level indicated: *$p < 0·05$; ****$p < 0·0001$.
†N = 6.
‡N = 6.

scenarios (in which two independent variables were manipulated), and differences in performance between novices and experts were more evident in the complex scenarios.

Scenario means (low fluid = 12·04 s, low heart strength = 11·81 s, and high resistance = 11·13 s) did not differ significantly, $F(2, 20) = 1·56$, $p > 0·05$. Trial means, 12·19 s (T1) and 11·12 s (T2), differed significantly in the ANOVA, $F(1, 10) = 12·44$, $p < 0·01$, suggesting further improvement within the test condition.

4.2.2. *Number of drugs used*: The number of drugs used by participants varied from 1–6. Means for the three display types were: 1·65 (EPD), 2·46 (IBD), and 2·38 (TSD). A 2 (skill level) ×3 (display type) ×3 (scenario) ANOVA showed a significant main effect of display type, $F(2, 20) = 5·45$, $p < 0·02$. A Tukey test revealed that EPD differed significantly from IBD and from TSD, $p < 0·05$, but IBD and TSD did not differ from each other. This is precisely the control performance pattern that had been predicted. However, means for novices (2·22) did not differ significantly from experts (2·10) in the ANOVA, $F < 1·0$, as had been expected.

Scenario means (low fluid = 1·81, low heart strength = 2·47, and high resistance = 2·21) were significantly different, $F(2, 20) = 5·08$, $p < 0·02$ (table 5). A Tukey test showed that low fluid differed significantly only from low heart strength, $p < 0·05$.

4.2.3. *Percentage of time in target range*: The percentage of time spent in the target range during a given trial varied from 0 to 95%. Means for the three display types were ordered as predicted: 81% (EPD), 61% (IBD), and 53% (TSD). A 2 (skill level) ×3 (display type) ×3 (scenario) ANOVA showed that these differences were significant, $F(2, 20) = 17·05$, $p < 0·0001$. Paired comparisons by Tukey test revealed that EPD differed from both IBD and TSD, $p < 0·01$.

Experts spent a slightly larger percentage of time (67%) in the target range than novices (63%); but the ANOVA revealed that this difference was not significant, $F < 1·0$. Scenario means (low fluid = 69%, low heart strength = 64%, and high resistance = 62%) also were not significantly different, $F(2, 20) = 1·55$, $p > 0·10$.

As predicted, when using IBD, novices were able to equal the performance of experts with TSD (58%). In contrast, when using TSD, novices maintained the system in target range only 48% of the time.

Scenario did enter into a significant interaction with display type, however, $F(4, 40) = 3{\cdot}38$, $p < 0{\cdot}02$. All participants solved the low fluid scenario equally well with IBD and EPD; for the remaining scenarios, only EPD resulted in a significant performance improvement. The interaction of skill level with scenario, $F(2, 20) = 3{\cdot}31$, $p < 0{\cdot}06$, and the three-way interaction of skill level, display type, and scenario, $F(4, 40) = 2{\cdot}28$, $p < 0{\cdot}08$, were marginally significant. To further clarify the three-way interaction, separate 2 (skill level) $\times$3 (display type) ANOVAs were done for each scenario.

A 2 (skill level) $\times$3 (display type) ANOVA using only low fluid scenarios revealed a significant main effect of display type, $F(2, 20) = 10{\cdot}92$, $p = 0{\cdot}0006$. A Tukey test revealed that TSD ($M = 50\%$) differed significantly ($p < 0{\cdot}01$) from both IBD ($M = 77\%$) and EPD ($M = 81\%$). The difference between means for experts (75%) and novices (63%) was marginally significant, $F(1, 10) = 4{\cdot}19$, $p < 0{\cdot}07$, as was the interaction between skill level and display type, $F(2, 20) = 3{\cdot}07$, $p < 0{\cdot}07$.

A 2 (skill level) $\times$3 (display type) ANOVA including only low heart strength scenarios also showed a significant main effect of display type, $F(2, 20) = 8{\cdot}85$, $p = 0{\cdot}002$. A Tukey test showed that EPD ($M = 82\%$) differed significantly ($p < 0{\cdot}01$) from TSD ($M = 54\%$) and from IBD ($M = 55\%$).

A 2 (skill level) $\times$3 (display type) ANOVA including only high resistance scenarios revealed only a significant main effect of display type, $F(1, 10) = 7{\cdot}23$, $p = 0{\cdot}004$. A Tukey test showed that EPD ($M = 78\%$) was significantly different from both IBD ($M = 51\%$; $p < 0{\cdot}01$) and TSD ($M = 57\%$; $p < 0{\cdot}05$).

5. General discussion

The present research was designed to test the ecological approach to interface design in a specific complex system, an intensive care unit. One subset of intensive care monitoring, haemodynamics, and one task—learning basic principles of haemodynamic monitoring—were selected to test the approach. The proposed guidelines of Bennett and Flach (1992) provided a way to evaluate the ecological display design approach systematically. A traditional strip-chart display that showed relevant process variables as distinct display elements (thus exemplifying Bennett and Flach's first design guideline) was compared with two enhanced displays—an integrated balloon display and an etiological potentials display. The integrated balloon display showed the anatomical constraints on three pressures and flows (and conforms to the second design guideline of Bennett and Flach). In the etiological potentials display, the three pressures and flows were shown integrated (i.e. nested) with their potential causes (or etiology), thereby making the hierarchical structure of the haemodynamic process available to the operator (and instantiating Bennett and Flach's third guideline).

The essence of the ecological (or inverse ecological physics) approach to interface design is to identify relevant system constraints and then make those constraints transparent to the operator. Results of this research showed that relevant haemodynamic variables had been identified and depicted in the displays in such a way as to allow experts to diagnose and treat common clinical problems accurately. Moreover, when clinical problems were presented in such a way that the anatomical constraints on pressure and flow were made visible in the integrated balloon display (Bennett and Flach's second guideline), experts and novices detected and solved problems more

quickly than with the traditional strip-chart display. When the need to detect those relationships was important for treatment co-ordination, as in the integrated, low fluid scenario, the effect on performance resulted in quicker and more accurate solutions. When the anatomical constraints on pressure and flow were shown nested within the relevant etiological constraints (per Bennett and Flach's third guideline), treatment control was further optimized in terms of speed, accuracy, and drug usage. In fact, with this final display enhancement, novices were able to achieve the same level of performance as experts.

As the integrated balloon display (IBD) and the etiological potentials display (EPD) presumably make increasingly available in the display system constraints that enhance diagnosis of changes in pressures and flow, it had been hypothesized that participants would take less time to initiate treatment when using EPD than IBD; and, similarly, take less time to initiate treatment with IBD than TSD. Second, because only EPD provides specific information about etiological constraints related to drug control, it was expected that only EPD would reduce the number of drugs participants used to correct observed problems. These two hypotheses were supported by the results of each experiment. Third, because effective treatment co-ordination depends on both accurate diagnosis and appropriate drug therapy, it was expected that treatment co-ordination (as measured by the percentage of time the system was maintained within target range) would be ordered as follows: EPD > IBD > TSD. The predicted rank order for EPD was found in all three experiments; the predicted order of IBD and TSD was found only in experiment 3.

The ecological approach to display design differs from the organismic approach by emphasizing environmental, or contextual, constraints on system performance. However, because the ecological approach focuses on the *interaction* of organism and environment, it assumes that overall performance in a complex system will be constrained further by operator characteristics and task goals. Therefore, it was expected that, because of their clinical experience, critical care experts would be able to detect the complex variables required for treating haemodynamic problems—even when presented with only discrete elemental displays. In contrast, it was expected that novices would have difficulty in detecting complex relationships between pressures and flows without significant enhancement by a display. This hypothesis was supported. In experiment 3, expert performance was quite good with all displays and the performance of novices improved significantly with each successive enhancement, that is, with the balloon display and the etiological display.

The finding in experiment 3 that experts did not take longer to initiate treatment, as had been expected on the basis of the authors' and others' previous experimental results, is probably due to two factors. First, in this experiment, the authors explicitly asked participants to correct the observed problem as quickly as possible. In previous experiments (e.g. Effken 1993), experts' performance was found to be highly sensitive to experimenter-imposed task requirements such as maximizing speed and minimizing drug usage. That is, experts modify their natural drug control patterns in conformity with the experimenter's demands. Second, in the clinical setting, expert clinicians learn to be very cautious in medication usage. In previous experiments it has been observed that novices who have no clinical background (for example, psychology undergraduates) demonstrate no such constraints on their drug administration. In the experiments reported here, the 'novices' in experiments 1 and 2 began treatment earlier and used, on average, one more drug than the 'experts' and 'novices' in experiment 3. In experiment 3, however, the 'novice' group was

composed of nursing students who were in their senior year with previous (albeit limited) experience in the critical care setting. It is likely that this acquired drug knowledge acted to constrain the novices to be more cautious in their administration of drugs and, therefore, more like the experienced critical care nurses that composed the 'expert' group. Presumably, these two factors together made the treatment initiation times of the two groups similar.

It had been expected that showing the anatomical constraints on pressure and flow would enable observers to predict more accurately how a change in one area (for example, right atrial pressure) would affect cardiac output. Participants' quicker problem detection with the balloon display suggests that showing the inherent connectivity does indeed help performance. However, no information was available in the integrated balloon display to direct their choice of drug therapy because the etiological factors, at which therapy is directed but which lie at another level within the haemodynamic hierarchy, were not shown. As a result, the number of drugs participants used to correct the problem identified with IBD was not reduced from the number used with TSD (and, for the non-clinician participants in the low heart strength scenario condition in experiment 2, fewer drugs were used with TSD). Although not statistically significant, this trend also was seen in experiment 3, but only for the novice group. Experts used fewer drugs with IBD than with TSD to solve the low heart strength scenario. This finding suggests that experts look for and can utilize the information about cardiac output that is available in IBD, but that novices may need to have the salience of that information enhanced further.

Results also indicate that the nature of the task further constrains how information should be displayed. It had been anticipated that the more globally distributed fault characteristics of the low fluid scenario would require more data integration and therefore make that scenario more difficult to solve with the non-integrated strip-chart display. That proved to be the case. This result is similar to the findings reported by Buttigieg and Sanderson (1992) and by Wickens *et al.* (1985); see also Bennett and Flach (1992) for an excellent review of experimental findings when different research methodologies are used to compare performance on integrated and focused tasks for configural and separate displays; and Gillie and Berry (1994). Since complex system problems are rarely restricted to only one site, displays that can facilitate integration should have an advantage in complex domains.

Some researchers have identified a cost to using integrated displays in focused tasks, that is, when the task requires using separate sources of information within the display (Carswell and Wickens 1987). Others (Buttigieg and Sanderson 1992) have found nominally improved performance in focused tasks as well. The present results suggest that, in general, the integrated displays used did not result in a performance cost for focused problems. However, the problems encountered by experts using the integrated balloon display in the high resistance scenario condition and by novices using the same display in the low heart strength scenario condition suggest that the answer to this question may require looking at all the sources of constraint (task, display, and observer).

The ecological approach to display design seeks to support skilled operator performance by building display geometries specific to the task-relevant properties of the task domain (Bennett and Flach 1992). Although the authors sought to capture in the experimental paradigm one set of tasks relevant to the critical care domain, it is clear that this experimental task is considerably simpler than the reality facing clinicians. Whether the results will generalize beyond this rather restricted setting

remains to be seen. The present design task was simplified considerably by having the relationship of pressure and flow symptoms (dependent variables) to the etiological factors (independent variables) captured formally by the Guyton equations. Clearly, one does not always have such a 'neatly tied package' when one presumes to capture the relevant relationships of a domain in a display.

Taken together, the results reported here offer preliminary support for the ecological interface design approach and support the conclusion that, to facilitate monitoring and control in complex systems, designers must (a) identify relevant process variables in the task, (b) organize those elements so that their relationships correspond to higher-order system constraints, and (c) nest the relationships, or symmetries, of the displays in ways that reflect accurately the hierarchical structure of the process (Bennett and Flach 1992). The results indicate that it is not enough simply to display relevant process variables, as traditional approaches are prone to do, for only experts can compensate for the lack of integration in the display. Neither is it enough to organize those display elements in such a way as to show the higher order system constraints at one level only, although this design strategy can facilitate performance to some extent. However, if system performance is to be optimized and the cognitive load on the operator maximally reduced, then the constraints shown in the display also must reflect the hierarchical structure of the process—and must show those constraints at the hierarchical level needed for control.

The results confirm that constraints can be identified and exploited—not only in the system to be controlled, but also in operator characteristics and in the goal to be achieved. Moreover, these three separate sources of constraints can interact to affect operator performance (for example, as in the three-way interaction of skill level with display type and scenario for percentage of time in target range in experiment 3). This result underlines the importance of matching the interface with the task *and* the user (see Bennett *et al.* 1993, Flach and Vicente 1989, Vicente and Rasmussen 1990, for similar conclusions). Only when all these requirements are met can the benefits of interface technology be maximized and operator stress minimized. Under conditions in which the inverse ecological physics problem is solved, the ecological approach to interface design appears to meet these requirements.

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Appendix. The FORTRAN program (Guyton 1980) used as the engine for the haemodynamic monitoring and control displays.

```
C Initial conditions
      T = 0
      I = .001
     FA = 5
     FC = 5
     FV = 5
     VA = .85
     VV = 3.25
    VRA = .1
     CA = .00355
     CV = .0825
    CRA = .005
     RA = 19.34
     RV = .74
     PA = 100
     PV = 3.7
    DVA = 0
    PRA = 0
    DVV = 0
   DVRA = 0
      VAO = .495
     VRAO = .1
      VAE = .355
      VVE = .3
     VRAE = 0
      PGA = 96.3
      PGV = 3.7
      FAN = 5
       HS = 1
C
  100 VRAE = VRA - VRAO
      PRA = VRAE/CRA
      CALL FUNCTN (PRA, FAN, FUN1)
      FA = FAN * HS
      DVA = FA - FC
      VAE = VA - VAO
      PA = VAE/CA
      PGA = PA - PV
      FC = PGA/RA
      DVV = FC - FV
      VVE = VV - VVO
      PV = VVE/CV
      PGV = PV - PRA
      FV = PGV/RV
      DVRA = FV - FA
      VA = VA + I * DVA
      VV = VV + I * DVV
      VRA = VRA + I * DVRA
      Return to 100
```