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ORIGINAL ARTICLE

Anne Miller

A work domain analysis framework for modelling intensive care unit patients

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Abstract Work domain analysis (WDA) has been applied to a range of complex work domains, but few WDAs have been undertaken in medical contexts. One pioneering effort suggested that clinical abstraction is not based on means-ends relations, whereas another effort downplayed the role of bio-regulatory mechanisms. In this paper it is argued that bio-regulatory mechanisms that govern physiological behaviour must be part of WDA models of patients as the systems at the core of intensive care units. Furthermore it is argued that because the inner functioning of patients is not completely known, clinical abstraction is based on hypothetico-deductive abstract reasoning. This paper presents an alternative modelling framework that conforms to the broader aspirations of WDA. A modified version of the viable systems model is used to represent the patient system as a nested dissipative structure while aspects of the recognition primed decision model are used to represent the information resources available to clinicians in ways that support 'if...then' conceptual relations. These two frameworks come together to form the recursive diagnostic framework, which may provide a more appropriate foundation for information display design in the intensive care unit.

Keywords Work domain analysis · Abstraction decomposition space · Natural systems · Viable systems model · Recognition primed decision model · Recursive-diagnostic framework

Abbreviations ADS: Abstraction decomposition space · DST: Dissipative structures theory · HIV/AIDS: Human immunodeficiency virus/acquired immunodeficiency syndrome · ICU: Intensive care unit · RDF: Recursive diagnostic framework · RPD: Recognition primed decision model · R-VSM: Revised viable systems model · VSM: Viable systems model · WDA: Work domain analysis

A. Miller
ARC Key Centre for Human Factors,
The University of Queensland,
4072 St Lucia, QLD, Australia
E-mail: amiller@humanfactors.uq.edu.au

1 Introduction

In medical intensive care units (ICUs) patient illness is characterised by derangements in the bio-regulatory processes that govern physiological functioning. Patients are admitted to an ICU so that their physiological processes can be supported while the causes of bio-regulatory failure (e.g. overwhelming bacterial infection; Worthley 2000) are addressed. Ideally and with time, medical and nursing support and the removal of the triggers of illness allow the patient's own bio-regulatory processes to resume autonomous, adaptive regulation. Bio-regulatory processes and the reasons for their failure are the work domain upon which clinicians act.

In addition, critically ill patients are admitted to ICUs for extended periods of time. Thus effective physiological support requires the coordination of care delivered by temporally distributed teams. Communication is central to coordination yet the information artefacts to support temporally distributed communication are often lacking (Xiao and the LOTAS Group 2001; Gopher et al. 1989). A major problem in the design of patient information representations is the lack of a framework that would help to organise complex information resources in a way that makes the bio-regulatory processes of patients and the means for action visible to clinicians.

This paper presents a framework for modelling and mapping available information resources to bio-regulatory processes that may be useful in information design. The framework is inspired by Rasmussen et al.'s (1994) work domain analysis (WDA), which has gained acceptance for modelling complex socio-technical systems. WDA has been applied to various domains, including industrial process control (Jamieson and

Vicente 2001; Reising and Sanderson 2002a, b) and defence (Naikar and Sanderson 2000; Burns et al. 2002; Bisantz et al. 2003).

Other approaches have been used for designing information representations in medical contexts. Powsner and Tufte (1994, 1997) designed information representations for general and psychiatric patients. While the specific design elements are elegant the overall design assumes a level of diagnostic certainty that may be inappropriate for ICU patients with emergent pathologies. In addition, the proximal relations between some elements in the design (the placement of white blood cells next to psychosis, haloperidol and temperature) do not correspond to physiological relations, which may make problem solving difficult in novel situations. Taking a different approach, Melles and Freudenthal (2003) used participatory design techniques to elicit information from ICU nurses about the design of medical equipment. This study drew on the self-reported experiences of nurses but provided no framework for modelling patient information more generically. None of these attempts outlined an organising framework for the design of information resources. Without a framework for design that informs the underlying structure of information and the assumptions made about its use, it may prove difficult to assess the usefulness of the representations beyond the experiences that informed them. Such designs may also be flawed when used in non-routine situations where an understanding of constraints and boundary conditions becomes central to knowledge-based practice (Vicente 1999).

WDA is a formative modelling approach (Vicente 1999) that has advantages over the normative or descriptive analytical methods used by others (Melles and Freudenthal 2003; Powsner and Tufte 1994, 1997) because it allows a complete description of the work domain, its object resources, constraints, boundaries and possibilities for action prior to a consideration of the tasks that might be undertaken within the work domain. The need for a complete inventory of available resources is especially important when designing information representations for the ICU: (a) because clinical tasks need to be tailored to fit the dynamics of individual patients; and (b) because information representations need to accommodate all available resources so that they may be evaluated and selected given particular circumstances. In an information representation based on a formative approach, clinicians would be free to tailor tasks based on knowledge about a particular patient's pathophysiology, using the complete inventory of resources and constraints that might be relevant for action. For these reasons, performing a WDA would seem to be an essential step because it promises to provide information essential for design.

In two critical care WDAs, both Sharp (1996) and Hadjukiewicz (1998) defined patients as the systems at the core of the work domain, because each patient represents an independent work domain to clinicians. In the ICU, separate patient bays are set up to meet the specific needs of admitted patients and to reduce chances of cross-infection. This paper also focusses on patients as the system at the core of the ICU work domain. However, when attempting to apply WDA to patients as work domains, it became apparent that the abstraction–decomposition space (ADS) framework for performing WDA was not capturing important characteristics of the patient domain. Difficulties in applying the ADS to work domains may not be limited to the ICU. Lind (2003) for example identifies a variety of issues. Lind proposes a number of modifications to the ADS, and calls for greater conceptual clarity in its formulation. In the present paper it is not argued that the general principles underlying WDA are not applicable but rather that a different WDA modelling formalism may be more useful for describing patients as work domains nested within the broader ICU.

The arguments supporting this view are presented in five sections. Section 2 reviews the ADS. Section 3 examines two studies that illustrate difficulties that arise when the ADS is applied to patients. Section 4 presents a theoretical basis for an alternative WDA formalism. Section 5 presents an alternative formalism that still conforms to the principle that a WDA should describe a work domain as a field of available resources, constraints and possibilities for action independently of any particular worker, automation, event, task, goal or interface. These factors are addressed in subsequent analyses within a broader cognitive work analysis (Rasmussen et al. 1994), the results of which will be reported elsewhere. In Sect. 6 the paper concludes by setting out a research agenda for developing an information representation for the ICU based on the framework presented in this paper.

2 The abstraction–decomposition space

Rasmussen and colleagues developed the ADS as a result of accident and incident investigations associated with nuclear power plants (Rasmussen and Jensen 1973; Rasmussen 1979, 1983, 1985). Rasmussen observed that the errors human operators were making could only be understood in terms of the operators' mental operations and he set out to better understand these. Rasmussen found that operators' conceptualisations of their work domains could be classified using two different dimensions: abstraction and decomposition. These dimensions form the axes of the ADS matrix and are described below so that the methodological but not philosophical divergences described in the later sections of this paper can be understood as emerging out of the existing framework.

2.1 The decomposition (aggregation) hierarchy

According to Rasmussen (1986) traditional hierarchies used in systems thinking made no distinction between decomposition (aggregation) and abstraction, whereas the evidence from verbal protocols and incident reports suggested that operators thought of the work domain in different conceptual languages (abstraction) as well as with broader or narrower focus (decomposition). Rasmussen (1986, p. 14) defined decomposition as "a hierarchy of parts, ranging from elementary components [...] through equipment such as pumps and motors to the complete plant". The advantage of thinking of a work domain in terms of aggregation is that it allows operators to limit their field of attention, letting them focus on one part in detail while remaining oriented to the broader context without being overwhelmed.

2.2 The abstraction hierarchy

The structure and the psychological relevance of the levels of the abstraction hierarchy are illustrated to the right of Table 1. Purpose-based reasons explain why functions, processes and objects at lower levels exist. In contrast, physically based causes explain how purposes, priorities and functions at higher levels are achieved, and so facilitate predictions about the effects of breakdown at lower levels of the abstraction hierarchy.

The kind of industrial processes investigated by Rasmussen and colleagues are controlled to achieve human and societal purposes. Industrial processes are "bound by the laws of control" (Vicente and Rasmussen 1992, p. 590), as represented in the closed loop model. In closed loop control the operator's task is to align the *actual state* of a process with the *target* or desired state by manipulating input actions. The extent to which the actual and target states are aligned reflects the extent to which system processes are controlled.

Powers (1978) argues that problems can arise when the closed loop model is applied to natural systems, such as humans. Powers refers to an 'input blunder' which involves confusion about the status of reference inputs—the target states in a closed loop control model. According to Powers, in natural systems there are no reference inputs; there are only sensory inputs. In artificial systems, reference inputs are externally imposed. In humans, reference inputs arise out of inner conceptualisations. In engineered systems the physical system is an instantiation of 'purposes' that arise out of the theoretical knowledge of process engineers and the economic or human service objectives of process owners. These 'purposes' must be communicated to human operators for effective system operation and control.

The abstraction hierarchy serves this latter function very well. The 'reasons' or purposes defined in the abstraction hierarchy serve as reference inputs—conceptual tools provided by engineers and process owners that allow operators to search through a physical work domain within purpose-based constraints.

2.3 The abstraction–decomposition space

The abstraction hierarchy and decomposition hierarchy form the vertical and horizontal axes of the ADS (Rasmussen et al. 1994; Vicente 1999; Sanderson 2003). All levels of abstraction apply to all levels of decomposition. The relationships between the cells in the body of the ADS are also important and are based on why, what, how or means–ends relations.

2.4 Conclusion

In summary, the ADS had its origins in power plant accident investigations. In this context Rasmussen and colleagues found that operators conceptualise their work domain in terms of decomposition and abstraction. The contents of higher levels of abstraction supply operators with reference or target inputs; they also define when a

Table 1 Levels of the abstraction hierarchy (Rasmussen et al. 1994)

Level of Abstraction*	Description**	Reasons/causes
Functional purpose	Properties necessary and sufficient to establish relations between the performance of the system and the reasons for its design, that is the purposes and constraints of its coupling to the environment	Reasons Purpose based
Abstract function	Properties necessary and sufficient to establish priorities according to the intention behind design and operation: topology of flow and accumulation of mass, energy, information people monetary value.	
Generalised functions	Properties necessary and sufficient to identify the functions which are to be coordinated irrespective of their underlying physical processes	
Physical function	Properties necessary and sufficient for control of physical work activities and use of equipment: to adjust operation to match specifications or limits; to predict response to control action; to maintain and repair equipment.	
Physical form	Properties necessary and sufficient to classification identification and recognition of particular material objects and their configuration; for navigation in the system	Causes Physically based

system is controlled—that is, when it operates within range of its reference inputs.

3 WDA in the intensive care unit

Despite its popularity, the WDA framework has seldom been applied in medical contexts. This section presents two studies that have applied aspects of the ADS described above to medical contexts. Based on the work of Rasmussen et al. (1994), Sharp (1996) developed an ADS for neonatal intensive care and Hajdukiewicz (1998) extended the ADS to anaesthesia. The process by which these ADSs were developed is representative of similar approaches used by researchers in other fields (Jamieson and Vicente 2001; Reising and Sanderson 2002a, b; Naikar and Sanderson 2000; Burns et al. 2002; Bisantz et al. 2003). However, only Sharp used his ADS to develop a preliminary information display.

While Sharp's (1996) and Hajdukiewicz's (1998) studies are both pioneering, upon close examination they raise issues about whether the ADS is the most appropriate formalism when the patient is at the core of the analysis.

3.1 Sharp's initial representation of a neonatal ICU (NICU) work domain

In the tradition of Rasmussen's (1979) close examination of practitioner conceptualisations, Sharp (1996) began his research by investigating whether physicians use abstraction to conceptualise critical care work domains. Based on workplace observations and structured interviews, Sharp initially presented the four-level abstraction hierarchy shown in Table 2.

Sharp's (1996) inclusion of 'diseases and disorders' in his abstraction hierarchy is its most notable feature. However, Sharp's (1996, p. 107) conclusions about his abstraction hierarchy are also important. He concluded that his abstraction hierarchy "provided more evidence to the use of abstraction by the physicians [...] however, the means–ends relationships found in the abstraction hierarchy are not evident in the abstraction levels". Sharp (1996) did not explore this observation any further, nor did he explain why he abandoned his initial ADS. However, the fact that Sharp included diseases or disorders—or more accurately diagnoses—in his abstraction hierarchy and his conclusions about means–ends abstraction are significant and worth exploring further. In the following section we briefly examine medical diagnoses and their implications for abstraction.

3.2 Diagnoses and clinical abstraction

The concept of diagnoses pervades medical and nursing training and reflects the structure of medical, as opposed to simply physiological, knowledge. In medical textbooks, diagnoses—for example, pneumonia—include concepts such as the probable causes of disease (aetiology), pathophysiological processes (pathogenesis and pathophysiology), signs and symptoms (clinical manifestations), likely outcomes (prognoses), and possible therapeutic interventions (treatment). Medical diagnoses are therefore templates that are developed through repeated observations that are made, reported, and finally agreed upon in forums such as the Society of Critical Care Medicine Consensus Committee as representing a unique physiological dynamic (McCance and Huether 1998). The US National Institute of Health's (2001) history of the formal classification of HIV/AIDS is

Table 2 Sharp's (1996) abstraction–decomposition space

Abstraction (Abstract → Concrete) / Decomposition (Whole → Part)				
Global Goals	Stabilise the patient	Stabilise systems: Body temperature, Cardiac function, Pulmonary function, Metabolism.		
Disease and disorders		Body system classification: pulmonary disease, cardiac disease	Specific disease: RDS, PPHN, Sepsis	
Physiology		Processes: oxygenation, ventilation	States of subsystems: Respiratory insufficiency, Cardiac insufficiency	States of physiological variables: Tacypnea; Bradycardia; Hypoxemia
Anatomy				Body structure: Heart location and size, heart pumping

typical of the process of defining diagnoses that involves the repeated observation of patterns of inputs correlated with outputs.

Ashby (1956, p. 86) observed that the repetitive observation of patterns of inputs correlated against outputs is characteristic of black box problem solving. A black box is a system "whose internal mechanisms are not fully open to inspection". By manipulating inputs and observing output effects, observers make deductive inferences about what might be occurring within the 'black box'. In practice, this leads to further input manipulation to confirm or refute the initial inference. In this sense, ICU patients are black boxes whose inner workings are not fully open to inspection because their physiological dynamics are not always known and because some processes cannot be sensed.

Ashby (1956) further proposed that black box problem solving proceeds by a series of 'if...then' hypotheses. In medicine, diagnostic templates that have been developed over many years are conceptual templates that support 'if...then' hypothetical relations. For example, *if* a patient is assigned the diagnosis of asthma, *then* the signs and symptoms of asthma should be or were present and should be relieved using asthma-related therapies. *If* the patient's symptoms are not those associated with asthma and/or are not relieved as expected, *then* an alternative diagnosis may be considered.

Thus the structure of medical knowledge is founded on a highly systematised approach to black box problem solving that continues today. The outputs of this approach (diagnostic templates) provide a basis for abstract conceptualisation that supports 'if...then' inferential reasoning. Sharp's initial ADS therefore reflect the systems of thought—clinical abstraction—used by clinicians who are responsible for intervening on critically ill patients. We will return to this point when discussing the diagnostic framework presented in Sect. 5.3.

3.3 Hajdukiewicz's ADS in anaesthesiology

Whereas Sharp (1996) began his research with a qualitative exploration of physician abstraction, Hajdukiewicz (1998) began with an analysis of medical representations of normal anatomy and physiology and concluded that these were inappropriate as a basis for WDA because they mix system structure with control functions. Although less attention is paid to this concern in later work (Hajdukiewicz et al. 2001), no distinction is made between internal bio-regulatory processes and the intervention processes that might be undertaken by clinicians. While this may present few problems for anaesthesia, where the patient's bio-regulatory processes can for the most part be assumed to be operating within normal boundaries, it is a critical distinction in the ICU where patients are admitted because bio-regulatory processes may or have become compromised.

Hajdukiewicz (Hajdukiewicz 1998; Hajdukiewicz et al. 2001) modified Sharp's (1996) final abstraction hierarchy and replaced his 'Transport, storage and control' level of abstraction with a 'physiology' level of abstraction (see Table 3). Sharp's (1996) abstraction hierarchy makes no distinction between clinical control and bio-regulation, but both are represented. The 'Balance' level of abstraction for example could apply equally to internal patient dynamics or to interventions undertaken by a clinician. Clinical control and bio-

Table 3 Sharp's (1996) and Hadjukiewicz's (Hadjukiewicz 1998, Hadjukiewicz et al. 2001) abstraction hierarchies

Rasmussen's abstraction hierarchies	Sharp's (1996, p. 109) final abstraction hierarchies	Hajdukiewicz et al. (2001, p. 84)
Functional purpose	*Purposes*: homeostasis-maintain internal environment	*Purposes*: physiological purposes governing the interaction between the patient and the medical environment. (e.g. homeostasis, adequate perfusion, circulation, oxygenation)
Abstract function	*Balance*: to maintain the internal environment the supply and demand of nutrients must be balanced	*Balances*: concepts necessary for setting priorities and allocating resources to the generic physiological processes (e.g. salt/water, oxygen supply/demand, electrolytes)
Generalised function	*Processes*: the processes that connect the chambers that are in balance. Processes correspond to regulated flows of oxygen	*Processes*: generic physiological processes that are to be coordinated irrespective of the underlying physiology and component configuration (e.g. circulation, perfusion, oxygenation diffusion, osmosis)
Physical function	*Transport storage and control*: the components that make up processes and the storage chambers	*Physiology*: the physiological functions available to establish and maintain the processes (e.g. the functioning of organs)
Physical form	*Physical form*: the actual arrangements and interconnections of the various body sub-systems	*Anatomy*: specific anatomical structures (e.g. the location, appearance, form and material structure of organs)

regulation are implicitly included. In contrast, Hajdukiewicz's (Hajdukiewicz 1998; Hajdukiewicz et al. 2001) abstraction hierarchy appears to represent regulation from the clinician's perspective only. Bio-regulatory processes do not appear. The remainder of this paper presents an alternative way of representing the patient that puts bio-regulation at the centre of the modelling effort because this is what ICU clinicians work on.

3.4 Conclusions

In summary, both Sharp and Hadjukiewicz apparently experienced challenges when applying Rasmussen et al.'s (1994) ADS formalism for WDA to critical care work domains. A possible reason for these challenges may lie with the nature of living systems. In order to evaluate this conjecture we need to know more about the characteristics of living systems and their bio-regulation. Section 4 explores the nature of autonomous biological systems with the goal of defining the most appropriate architecture for a WDA of the ICU patient.

4 The nature and regulation of biological systems

This section explores what is currently understood about the characteristics of autonomous living systems and the nature of their regulation and argues that these characteristics must be accommodated in any representation of the ICU work domain. The singular difference between stable control in engineered systems and stability in biological systems is that biological stability is not determined by externally imposed reference inputs. This is in contrast to industrial control systems discussed by Lind (2003) where objectives and boundaries of operation are ultimately set by engineering and design decisions that are external to the system itself. Even the automated industrial control systems that Lind (2003) discusses serve external human purposes.

If bio-regulatory processes are to be included in a WDA because patients' internal bio-regulatory processes are the fields upon which clinicians act in the ICU, then it is possible that gradient dissipative structures theory (DST) might provide a theoretical basis for modelling and ultimately for design. In order to explore this contention, the following section presents the broad characteristics of biological systems that, according to current theorising, are a consequence of non-linear thermodynamic processes.

4.1 The characteristics of biological systems

Davies (1998) maintains that life seems to involve two crucial factors, metabolism and reproduction, which depend on a number of intrinsic 'qualities'. The first intrinsic quality is autonomy. Collier (1999) maintains that a system is autonomous if it uses its own information to modify itself and its environment to enhance its survival. Autonomous systems are also independent and maintain their cohesion in the face of internal and external fluctuations. Independence is not passive. Living systems actively maintain themselves so that they can develop, grow and repair themselves (Varela 1979; Collier and Hooker 1999).

The cohesive autonomy of living systems entails their second intrinsic quality: they are complex. According to Davies (1998) and to Collier and Hooker (1999) the complexity of living systems is organised, because only through organised complexity can organisms maintain cohesion while still being able to adapt to fluctuations. According to Collier and Hooker (1999), the kind of biological self-organisation that adaptation implies means that living systems can change their dynamical form. This is not a characteristic of non-living systems, which are constrained to behave according to defined rules of interaction with an environment. Davies (1998) and Collier and Hooker (1999) also maintain that information is the source of cohesive stability in living systems and that information increasingly appears to be processed by non-linear thermodynamic means, principally by means of dissipative structures. Because the model presented in this paper is motivated by dissipative structures theory, they are briefly summarised below.

Dissipative structures theory (Nicolis and Prigogine 1977; Kondipudi and Prigogine 1998; Schneider and Kay 1994, 1995) has its origin in Schrodinger's (1944) concept of negative entropy. A dissipative structure is comprised of a variable flow, a gradient (sourced ultimately from the organism's external environment) whose fluctuations are reduced by highly non-linear dissipative processes. Relative stability is achieved when dissipative processes are able to respond to minimise fluctuations in gradients. Bio-regulation fails when gradients exceed the self-organising capacity of a dissipative process to modify its processing behaviour to meet gradient demands or when the dissipative process itself fails despite relatively normal gradients. Evidence for bio-regulatory breakdown appears in the clinical signs of pathology. Recently, medical research has drawn on DST to understand the development of atherosclerosis (Lu and Zheng 1981); the development of cancer (Klimek 1990); intracellular metabolic processes (Schiffmann 1991; Toko et al. 1988); and the production of complex proteins (Harper et al. 1984). DST is therefore an increasingly accepted approach to modelling bio-regulation and its breakdown.

4.2 Conclusions

In summary, the most fundamental characteristic of a biological system is its self-organising autonomy. Normally functioning bio-regulation does not require—nor is it governed by—externally imposed reference inputs as industrial control processes, whether automated or manual, are. Instead, ICU patients are biological systems with their own regulatory processes. Paradoxically for cognitive work analysis, the patient is both the work domain and its ultimate controller. Often in contrast to the operating room environment, the pathologies found in ICUs involve aberrations in the patient's internal regulatory processes to the extent that the body's cohesive autonomy is threatened (see Oh 1997 and Worthley 2000 for descriptions of such processes). The role of clinicians is to intervene using drugs or devices that either remove the causes of aberration (e.g. antibiotics) or moderate aberrant bio-regulation.

The implication of these conclusions for a WDA of the patient as the system at the core of the ICU is that it must be possible to represent the internal regulatory processes of the patient in any modelling framework. This is because these processes are an inherent part of the patient system and because these processes are the focus of clinical work. The remainder of this paper presents a WDA formalism that includes internal regulatory processes as part of the work domain, with a view to eventually informing the design of information displays that will support clinicians' work.

5 An alternative WDA formalism suited to the ICU

This section suggests an alternative formalism for performing a WDA centred on ICU patients. One dimension of the formalism represents the patient system (the recursive hierarchy) and the other dimension represents clinicians' diagnostic conceptualisations about that system (the diagnostic framework). The recursive hierarchy is grounded in cybernetics. Contemporary views maintain that cybernetics deals with complex systems such as organisms, ecologies, minds, societies and machines as multi-dimensional networks of cooperating information systems (Joslyn 1992).

Although computational cyberneticists use computer simulations to study real-world-like phenomena, there are relatively few frameworks for describing real-world cybernetic systems. Maturana and Varela (1970) and Varela (1979) consistent with the characteristics outlined in Sect. 4, present living systems as nested networks of interactive processes that are capable of reproducing themselves and their components (Varela 1979). The viable systems model (VSM) (Beer 1981) draws on Maturana and Varela's (1970) ideas and, in addition, defines the minimum set of interactive functions, independently of their realisation or form, required for viability. The following section presents the recursive hierarchy based on a modified version of the VSM.

5.1 The recursive hierarchy

In ICUs, clinicians work with pathology in functional and bio-regulatory processes. Beer's (1981) VSM can be used to map functional organisation and relationships. This section presents a modified version of the VSM as a descriptive framework for modelling biological functions and interconnections, followed by comments on its strengths and limitations for the present purpose.

5.1.1 The viable systems model

Although Beer (1981) applied the VSM to corporate management (Flood and Carson 1993; Espejo and Harnden 1989), the VSM was originally inspired by neurophysiology and hence has its origins in a study of the functional and regulatory behaviour of a living system. It may therefore be useful in describing patients as self-regulating or viable systems.

The VSM is based on a set of principles that appear to reflect the characteristics of living systems as outlined in Sect. 4. First, in the VSM 'control' is embedded, growing and evolving with the viable system. Second, bio-regulation involves the processing of fluctuating flows in a manner that is consistent with Ashby's law of requisite variety, which is essential to the VSM (Beer 1981). Ashby's law states that for, "appropriate regulation, the variety of the regulator must be equal to or greater than the variety in the system being regulated" (Principia Cybernetica Web dictionary, http://pespmc1.vub.ac.be/ASC/IndexASC.html, cited 15 March 2004). From a dissipative structures perspective, dissipative processes are 'regulators' that absorb or respond to changing gradients. Third, in line with the argument in Sect. 4, Beer (1981) maintains that viable systems are independent and autonomous. Finally, according to Beer (1981), Maturana and Varela (1970), Varela (1979) and Giampietro (2004) complex functional systems have a nested organisation, so that large-scale complex systems are comprised of smaller-scale complex systems. Maturana and Varela (1970) refer to nested levels as unities, which they also claim are recognisable by internal interactions that define the unity's boundary. However, neither Maturana and Varela (1970) nor Varela (1979) specify the types of interactions that define a unity. Beer's (1981) VSM serves this purpose; it defines the types of interactions within a unity that are required for viability without specifying the form of interactions which will vary across scale and species.

The VSM as Beer (1981) originally developed it is represented to the left of Fig. 1 and is comprised of five 'systems' whose functions are listed below:

1. *System 5* determines 'directions' and represents the viable system to its environment. System 5 also receives information from and directs System 4.
2. *System 4* monitors internal and external environmental states and communicates mismatches to System 5. System 4 also communicates 'instructions' to System 3.
3. *System 3* is internally focussed and, within System 4 instructions, is responsible for co-ordinating routine internal functions such as respiration.

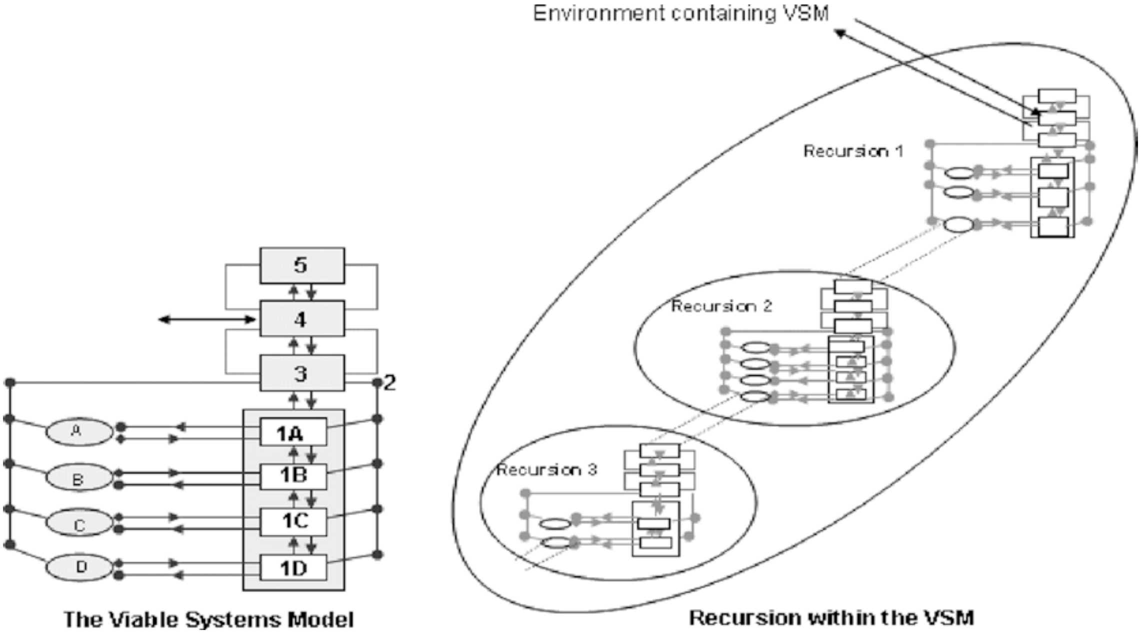


Fig. 1 The viable systems model

4. *System 2* is an integrative communication and distribution network between all System 1s and System 3.

According to Beer (1981), there are as many System 1s as are needed to perform the functions required for viability. All System 1s independently regulate and undertake their own internal interactions, which can again be categorised using the VSM structure.

The VSM presented in Fig. 1 was designed for corporate contexts. It needs to be somewhat revised if it is to represent human physiology in a useful way.

5.1.2 The revised VSM

The VSM's language can be problematic and the model is not defined in dissipative structures terms. Before we show how the VSM can be applied to physiology, we propose the following modifications.

First, Beer's (1981) use of the term 'system' can be confusing. For clarity the term 'Function' will be substituted for the term 'System'. Thus Beer's (1981) System 5 becomes Function 5 and so on. The term 'system' will be used only to refer to viable systems or to systems as normally understood.

Second, Beer (1981) did not include DST within the VSM, nor did he successfully specify the nature of communication between functions. Nonetheless, VSM Functions 5, 4, 3 and 1 can be understood as dissipative processes. Function 5 includes dissipative processes whose output gradients involve 'direction'; Function 4 includes dissipative processes that respond to internal–external gradients and so on. If Functions 5, 4, 3 and 1 are dissipative processes, then all of the 'arrows and lines' in Fig. 1 are gradients. By placing all gradients within Function 2 we will be able to chart gradient relations within and between recursions.

5.1.3 The R-VSM applied to human physiology

A complete model of how the R-VSM can be applied to human physiology is presented in Miller (2003) and was constructed with reference to Guyton and Hall's (1996) *Textbook of medical physiology*. Figure 2 shows the complete model defined to three levels of recursion for functions relevant to the ICU. This is not a complete model of human physiology.

A schematic representation of the VSM is shown at the top of Table 4; beneath this is a tabular representation of the level of the organism as a whole including, at the bottom of the table, the relevant chapters from Guyton and Hall's (1996) textbook.

In order to map physiological functions to the framework, the first task was to identify major 'organismic' level gradients (e.g. pH, tonicity, temperature) associated with Function 3, which is most relevant to the ICU given the types of pathologies found there (Oh 1997).

From this starting point, chains of gradients and their associated dissipative processes were traced through Guyton and Hall's (1996) textbook and were grouped to form the overall model shown in Fig. 2. Each Function in Table 4 was described using three sub-categories: gradients, physiological processes and anatomical structures. As gradient-process chains were identified they were cross-referenced against pathophysiology texts (McCance and Huether 1998; Oh 1997) to establish the well formedness of the mappings. Thus if, for example, pH is a gradient dissipated by respiratory processes, then aberrations in respiratory processes (e.g. emphysema, asthma) should show aberrations in pH, as is the case. Although the representations illustrated in Fig. 2 and

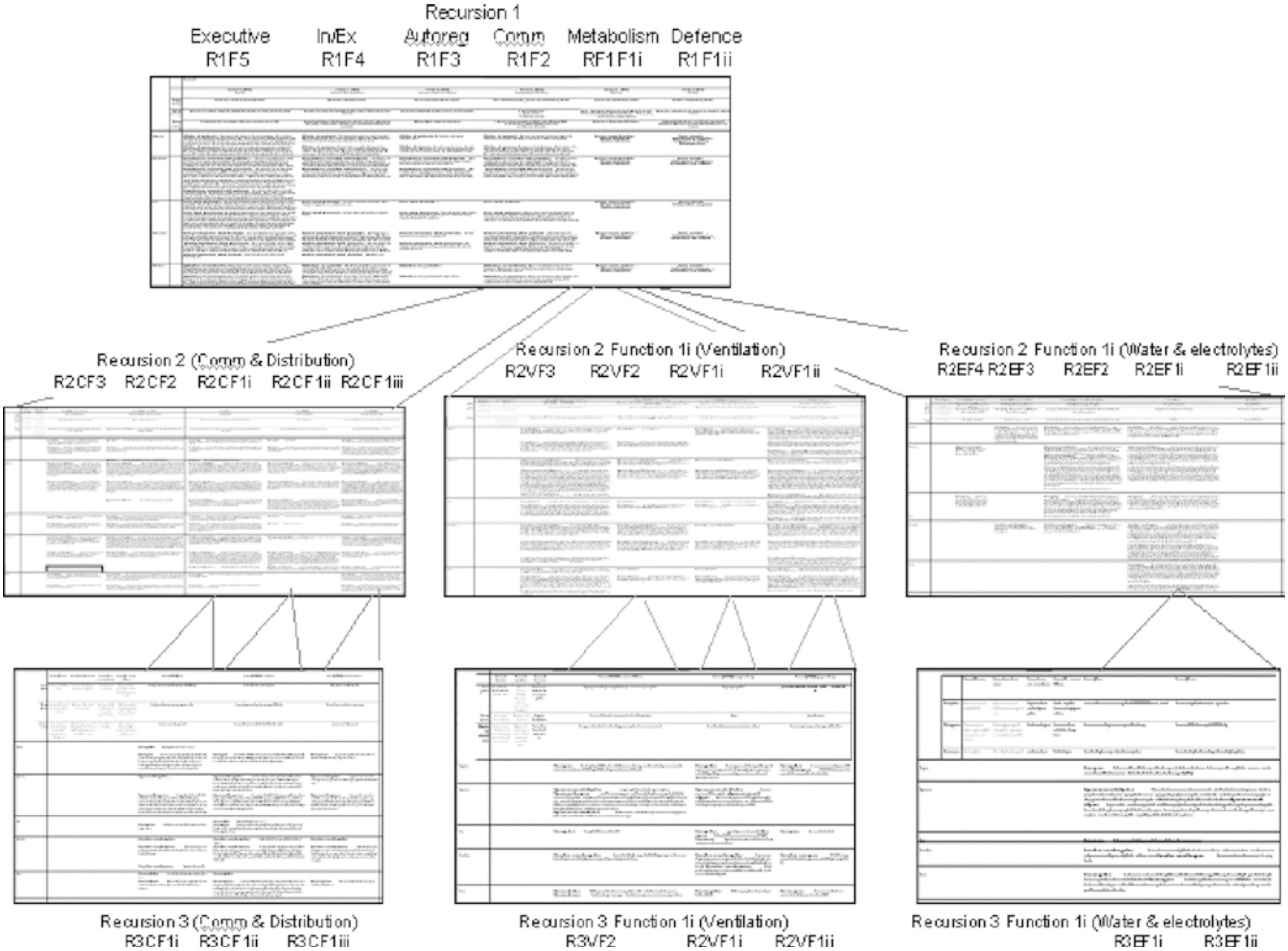


Fig. 2 Complete model to three levels of recursion (a readable version of the complete model is extremely large and can be accessed in soft copy from the author upon request)

Table 4 are unconventional, they do appear to accommodate medical physiology.

Table 4 has two other noteworthy features. First, Function 2 (communication and distribution) consists of neural, chemical and pressure gradients. This redundancy lets Function 2 respond to and smooth dissipative processes within and across recursive functions. Second, gradient-dissipative processes are not limited to specific anatomical arrangements. Several may be involved as illustrated for Function 4 and Function 2.

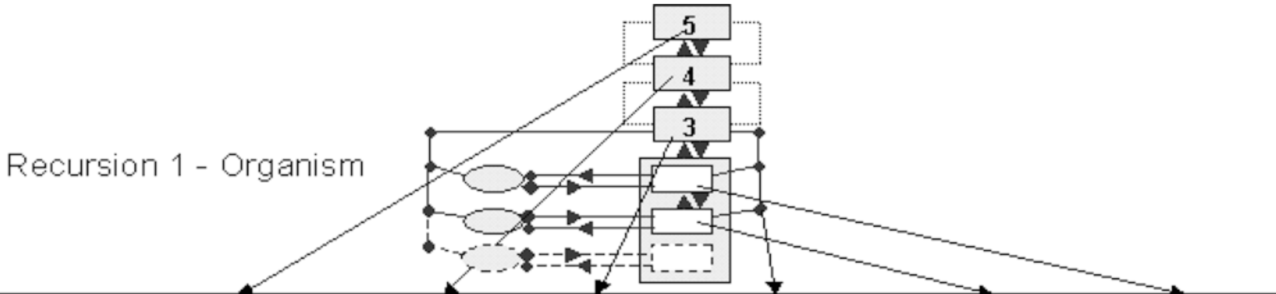
In the complete model (Miller 2003) each level of recursion represents a level of functional decomposition. The fact that each level represents functional decomposition rather than structural decomposition may seem counterintuitive to those who are practised in WDA but functional decomposition is a logical extension of the fact that physiological functions are fully contained and regulated within autonomous biological systems. Thus as for the ADS, moving from a higher level of recursion to a lower level involves 'zooming in' on lower level descriptions (Vicente 1999).

5.2 Conclusions

The R-VSM may provide a suitable framework for conducting a WDA when the functional organisation of biological systems must be considered. The advantages are fourfold. First, the R-VSM provides an integrated framework that does not depend on any particular state, process or activity, patient or disease process. Second, the R-VSM specifies the functions that are required for viability independently of the form of these functions and independently of whether these are known, unknown or incompletely known. Complete knowledge is not a modelling prerequisite. Third, the R-VSM accommodates important characteristics of physiology that are increasingly discussed by medical biologists, and finally, the R-VSM also allows a mapping of gradients, physiological processes and anatomy at each level of functional description.

The R-VSM is not always neatly applied, however. It can become difficult to identify executive functions at lower levels of recursion. It may be that physiological behaviour at this level is incompletely understood, that the R-VSM is inadequate at lower levels of detail or that it has been misapplied. Then again, in a conventional ADS functional purposes may be difficult to define at the

Table 4 Recursion 1 of human physiology



	Function 5. Executive	Function 4. Internal / External interface	Function 3. Internal automatic co-ordination	Function 2. Communication & distribution	Function 1i. Metabolism	Function 1ii. Defence
Gradients	Cortical neural activation gradients	Specific neural activation gradients	Specific activation and concentration gradients	Neural activation thresholds, pressure and concentration gradients	Pressure and concentration gradients	Biochemical concentration gradients
Physiological processes	Processes of cognition, judgement, planning. The initiation of voluntary motor movement	Processing and redirecting incoming sensory signals (external and internal)	Processing of information related to basic survival functions	1. Neural transmission. 2. Circulation. 3. Hormone secretion	Supply - Respiration, Ingestion / digestion, Waste processing - Defaecation, Urination. Utilisation & Storage - Protein, Fats, carbohydrates,	Haemostasis, inflammation, opsonisation etc, antibody / antigen reaction
Anatomical structures	Telencephalon	Diencephalon (thalmus / hypothalmus) and subcortical structures (eg pituitary, basal ganglia, circinate cortex) + Cortical areas associated with sensation and perception	Midbrain (Medulla oblongata, Pons Varoli)	1. Neural transmission pathways. (Spinal cord & Autonomic NS). 2. Cardiovascular network including blood volume. 3. Endocrine / Exocrine	Apparatus of: Respiration, GIT, Renal,.	Integument, Structures associated with coagulation, & inflammation. Structures associated with immunity (cellular and humoral)
	Guyton & Hall (1996) Chpt 54, 57, 58. Goldberg 2001	Guyton & Hall (1996) Chpt 48-53	Guyton & Hall (1996) Chpt 9, 18, 28, 41, 56	Guyton & Hall (1996) Chpt 18, 19, 60	Guyton & Hall (1996) various Units & Chapters	Guyton & Hall (1996) Unit VI

unit level of detail too. The R-VSM is also an unconventional representation. Chapanis (1961) maintains that usefulness is the criterion for a model's success, as distinct from truthfulness, which determines the success of a theory by the conventions of scientific falsifiability. The R-VSM is not a theory. It is a model, which remains to be evaluated by more thorough tests of its usefulness. So far, however, the R-VSM appears to usefully accommodate what is known about human physiology in ways that make it amenable to WDA and to information design (Miller and Sanderson 2003a, b, c)

5.3 The diagnostic framework

Researchers have developed abstraction hierarchies in different ways. Rasmussen (1979, 1986), Sharp (1996) and Burns et al. (2002) developed abstraction hierarchies based on the codified experience of workers in practice. Naikar and Sanderson (2001), Bisantz et al. (2002) and Hadjukiewicz (1998) developed abstraction hierarchies based on formal descriptions—system design specifications in the first two cases and scientific principles in the third case. Each approach resulted in an analysis that represented the structure of knowledge that was relevant to a particular domain, organised within the abstraction and decomposition dimensions of the ADS matrix.

The recursive hierarchy presented in the previous section represents the functional organisation of patients as physical systems but does not show how clinicians conceptualise ICU patients. Sharp's (1996) initial abstraction hierarchy provides some important clues: namely that diagnoses are important in clinicians' thinking. In Sect. 3 medical diagnoses were defined as formal templates. It was concluded that the diagnoses presented in pathophysiology textbooks represent the structure of medical knowledge in relation to critical illness. Reflecting this, Sharp's (1996) initial ADS suggested that diagnoses are the conceptual basis for clinician interaction with patients. It remains to show how this knowledge can be organised in abstract terms that can be related to patients.

5.3.1 The recognition primed decision (RPD) model

One way of organising information contained in medical textbooks can be developed from Klein's (1998) recog-

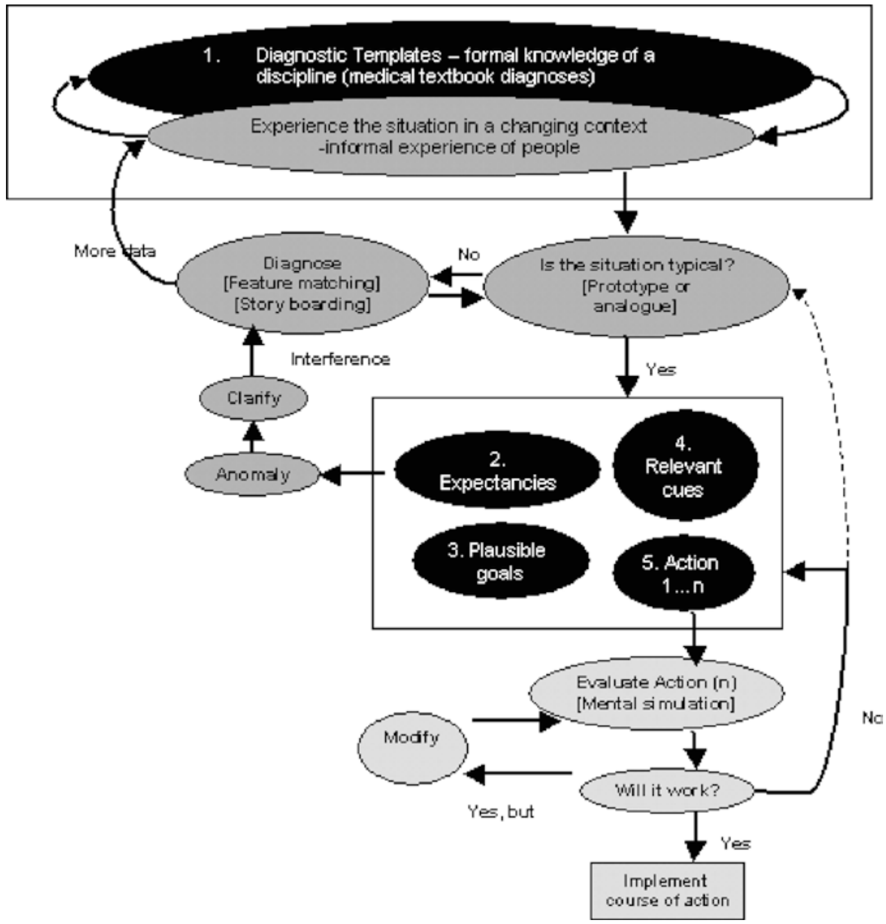


Fig. 3 Klein's recognition primed decision model

nition primed decision (RPD) model, which is presented in Fig. 3.

Elements within the RPD can be divided into two types that are represented by grey or black shading. The black nodes represent patient-related information resources and are therefore part of the WDA. The grey nodes represent processes that occur during decision making and therefore—as activity—are not part of the WDA. Instead, they would normally be represented in a control task analysis (Rasmussen 1986; Rasmussen et al. 1994). This is an important distinction.

As noted, the black nodes represent the information resources in object terms. They will now be discussed in turn as the fundamental conceptual building blocks of the proposed diagnostic framework.

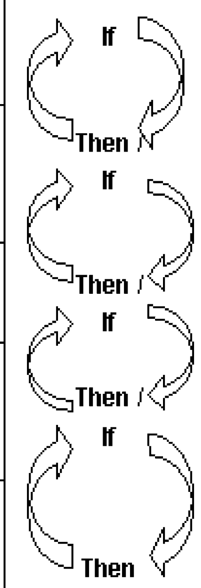
At the top of Fig. 3 is 'experience of the situation in a changing context'. The grey node represents the experience of individuals gained through repeated exposure to similar situations. However, behind and informing personal experience is the accumulated formal knowledge of the medical and nursing professions which, as discussed in Sect. 3, is represented in medical textbooks as diagnostic templates. Representative information resources include conceptual objects such as septic shock, respiratory failure, renal failure and so on. These diagnoses are not events or states; they are conceptual templates.

The second category is expectations. The resources that would be included in this category are information about pathophysiological trajectories and prognoses, such as '90% mortality rate after 5 days' or 'renal failure will recover in 4 days'. As in Klein's (1998) generic model expectations are cued by 'if...then' relationships from 'experience in the situation'. Thus, if a patient has asthma (diagnosis), then the patient will probably have shortness of breath (expectation).

The third category of information resources is plausible goals. This category is the inventory of possible plausible goals that could be cued in 'if...then' fashion by expectations. In the complete recursive–diagnostic framework (RDF), plausible goals are those that are made possible within each physiological function. At Recursion 2 (ventilation), which deals with the mechanics of breathing, a plausible goal might be to 'reduce work of breathing'. These goals are made possible as a direct consequence of the properties inherent in relevant dissipative processes or gradients in each function. It must be emphasised that plausible goals are not control tasks. In the RDF, plausible goals represent conceptual spaces of possibilities that are prescribed within diagnostic templates and made possible by levels of physiological functioning.

Table 5 The diagnostic framework

Psychological relevance	Klien's RPD	DF	Descriptions of elements	Possible relations
Conceptually abstract	Experience in the situation	Diagnoses	An inventory of clinical constellations. Informed by inventories of 'diseases' found in pathophysiological texts and clinical experience.	
	Expectancies	Expectations	An inventory of possible future states based on knowledge about pathological processes and outcomes; informed by pathophysiological processes described in medical texts and experienced in practice.	
	Plausible goals	Goals	An inventory of possible priorities or plausible goals based on formal knowledge about current and future states.	
	Relevant cues	Sensed information	Inventory of information cues that are available in the clinical environment; informed by signs and symptoms, or clinical manifestation sections of pathophysiological texts.	
Conceptually concrete	Actions	Effectors	Inventory of possible action interventions available in the clinical environment; informed by recommended interventions or therapies sections in pathophysiological texts. An inventory of effectors might include relevant drugs and devices	



The fourth category of information resources is relevant cues or sensed information which may be cued, again by 'if...then' relations. Relevant cues are measurable or observable pieces of qualitative and quantitative information. Such information might include parameters such as limb colour, blood pressure, tidal volume or respiratory rate.

The final category of information resource is actions or effectors. Effectors are the resources available for action. An inventory of effectors might include mechanical ventilator, haemofiltration unit and drugs such as noradrenaline, morphine and so on. Like plausible goals, each of these levels of abstraction represents a conceptual space made possible by physiological function.

The diagnostic framework is presented in Table 5. The first column illustrates the psychological relevance of the diagnostic framework in abstract terms. The top levels of the DF contain highly abstract conceptual levels of medical knowledge. Knowledge levels become more concrete towards the lower levels of the table. In the second and third columns are the categories of information resources as Klein (1998) originally named them and as they have been modified for the patient work domain. The fourth column defines each of the levels of abstraction and indicates where this information might be found in medical texts. The final column, based on Klein (1998), shows possible relationships between the levels. The result is a framework that formalises the way medical resources may be allocated, driven by diagnoses (Sharp 1996).

5.4 Strengths and limitations of the diagnostic framework

The diagnostic framework allows a complete categorisation of all information resources available to clinicians related to patients including higher-order conceptual resources such as diagnoses and expectations as well as more concrete resources such as discrete pieces of sensed information. Using the diagnostic framework these resources can be mapped directly to physiological functions.

Including plausible goals within the diagnostic framework, and thereby within part of a WDA, may raise questions for those familiar with cognitive work analysis. In the diagnostic framework plausible goals are simply the space of plausible goals made possible at different physiologically functional levels. They do not represent activity. It is, however, possible that plausible goals in the diagnostic framework may become the link to a control task analysis or even become subsumed within the same. This is an outstanding question that cannot be answered without a more detailed analysis of the control tasks that clinicians undertake.

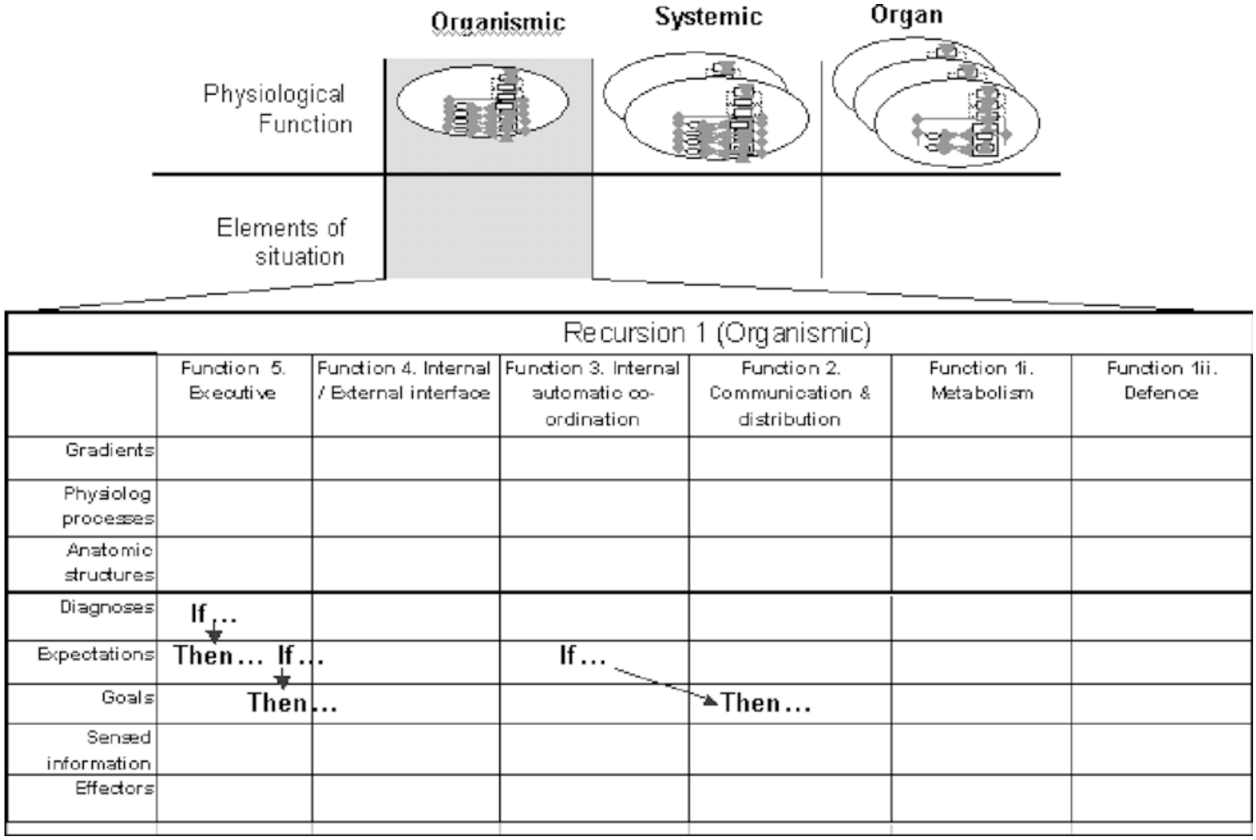


Fig. 4 The integrated RD framework

5.5 Recursive diagnostic framework

A WDA of the patient as the system at the core of the ICU needs to integrate the patient's intrinsic regulatory mechanisms with the superstructure of medical resources that make intervention possible. To achieve this, the recursive hierarchy and the diagnostic framework can be combined to form the RDF as shown in Fig. 4. The top section orientates the lower section within the VSM framework. The lower section of Fig. 4 shows the expanded RDF for Recursion 1.

Table 6 shows an extremely limited but illustrative example of a completed RDF based on a textbook description of the diagnosis cerebro-vascular accident (CVA) (stroke). Only relevant functional levels of recursion are included. In Table 6, the CVA diagnosis includes sub-diagnoses and expectations across different functions, representing the complexity of many diagnoses. For example, Functions 5 and 2 include diagnoses, which include death of brain tissue and a blockage in major arteries. Thus we can represent the range of possibilities, without representing any one situation.

Although the example in Table 6 represents a specific medical problem to show how the framework functions, the framework itself is independent of any specific patient context. Further diagnoses such as no injury, closed head injury, space-occupying lesions, and insults affecting Functions 3 and 4 can be added to build a fuller picture of the information resources available at this level of physiological functioning.

In this way the RDF presents the total information space available to clinicians. The elements of the diagnostic framework can be further broken down so that diagnoses specific to gradients can be differentiated from diagnoses associated with processes and with anatomy.

6 Prospects for use

The RDF is not intended to be a medical model, but instead is a framework for cognitive engineers to organise the information and resources that ICU clinicians need to better care for and communicate about the pathologies of ICU patients. The test of the RDF will therefore not be whether it is useful to ICU clinicians as a medical model, but instead whether the information representations cognitive engineers will develop from it are useful to ICU clinicians. This test will include subtests such as whether the RDF facilitates greater ease of representation, ease of use, and ease of translation into information requirements than a conventional ADS. While Sharp (1996) produced and evaluated a preliminary display with some qualified advantages over existing displays, Hajdukiewicz et al. (2001) did not address these issues.

As a first step towards developing an information representation based on the RDF, Miller (2003) tested whether the RDF was useful in defining an information

Table 6 Illustrative RDF of the cerebro-vascular accident based on Guyton and Hall (1996) and McCance and Huether (1998)

	Recursion 1 (Organism)			Recursion 2
	Function 5. Executive	Function 4. Internal / External interface	Function 3. Internal automatic co-ordination	Function 2. Communication & distribution
Gradients	Neural threshold and activation gradients	Neural threshold and activation gradients	Neural threshold and activation gradients pressure and concentration gradients	Pressure, chemical concentrations (pH, O2)
Physiological processes	Cognitive activites associated with planning judgement decision making (speech comprehension) and the initiation of voluntary movement	Processing and redirecting incoming sensory signals (external and internal)	Processing of information related to basic basic survival functions	Pressure driven perfusion; Osmosis, Diffusion
Anatomical structures	Telencephalon	Diencephalon (thalmus / hypothalmus) and subcortical structures (eg pituitary, basal ganglia, circinate cortex) + Cortical areas associated with sensation and perception	Midbrain (Medulla oblongata, Pons Varoli)	Cerebral circulatory network (Arterial, Venous, meninges [arachnoid], cerebral ventricles)
Diagnoses	Infarct areas of telencephalon downstream from occlusion.	Minimal or no effects; normal function	Minimal or no effect; normal function	Middle cerebral artery occlusion (thrombotic)
Expectations	Localised inflammation and tissue death leads to extended tissue damage(48-72hrs); cerebral swelling (upto 2 weeks for resolution). Possible reperfusion injury. Hemiplegia & hemiparesis.	No or transient sensory loss anticipated	No or transient loss anticipated	Depends on extent of occulsion and time to intervention; Fluid extravasation and impaired cerebral drainage
Goals	Minimise risk of further injury, Initiate treatment within 6 hours	None required	Respiratory support if needed.	Promote early reperfusion. Minimise cerebral oedema
Sensed information	Glascow coma scale higher order function scores e.g. orientation to time and place. Intracranial pressure monitoring. CT scan; MRI scans	Glaxcow coma scale sensory scores e.g. pupillary response to light	Glascow Coma scale reflex function scores e.g. Respiratory rate, depth, heart rate, blood pressure. Serum pH; CO2; HCO3	CT scans; Blood clotting and coagulation studies
Effectors	None recommended	None recommended	non-invasive support (oxygen via mask cannulae) Mechanical ventilation	Anticoagulants (heparin, warfarin); Anti-thrombotics (eg streptokinase);

architecture for such a representation. Using the video-cued recall debrief technique (Omodei et al. 2004, in press) she recorded and coded ICU doctors' and nurses' recall of handovers at which they were present. The coded transcripts were used to identify available information resources, which were then located within the RDF matrix. The completed RDF matrix became an inventory of information available to clinicians in relation to ICU patients. Based on relationships determined within the RDF matrix, a paper prototype information display was developed. Under experimental conditions the prototype was found to increase the breadth of nurses' perceptions of change events in terms of the number of patient parameters reported and lead to greater agreement among doctors as to the current state of a patient. These findings support conclusions that the prototype improved the situation awareness of nurses and common situation awareness among doctors (Miller 2003).

The outcomes of the current research program have presented a number of questions for future research. As the paper prototype moves towards an electronic version, questions remain about how time should be represented. Questions remain also about how an ICU information representation might support common situation awareness among temporally distributed nursing and medical team members. Finally, questions remain about the role that information representations might play in both promoting and reducing adverse patient outcomes.

7 Conclusions

Rasmussen et al. (1994, p. 4) stated that, "design has to be concerned with supplying objectives and resources to individuals who then solve their problems in a dynamic work space and flexibly change their preferred cooperative patterns". Thus the philosophical orientation to system design within cognitive work analysis is for workers to be allowed to adapt to changing circumstances within the boundaries of safety, efficiency and productivity made visible to them. WDA sets out the ‘topography’ of the information space upon which action can occur (Vicente and Rasmussen 1990; Vicente 1999). Vicente uses the land map metaphor to communicate the idea that within ‘topographical’ constraints, a range of different routes may be available for achieving the same objective. The RDF embodies the same aspiration. In the ICU clinicians should be able plot courses through an information space, being able to ‘see’ what the implications of intervention might be. The differences between the ADS and RDF formalisms are driven solely by the relative characteristics of the work domains of interest.

In the ICU, patient illness is characterised by aberrations in physiological and bio-regulatory processes. This is the domain upon which clinicians work. The RDF makes visible the functional nature of the internal patient system to the extent that this can be known and links the full complement of information resources available in the ICU to the internal patient system. This provides a foundation for information representation design, which may then be used as a basis for further studies associated with the effects of information artefacts in supporting medical and nursing team coordination.

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