Introducing Intelligent Systems into the Intensive Care Unit: a Human-Centred Approach

M. Melles*, A. Freudenthal*, C.A.H.M. Bouwman**

* Dept. of Industrial Design, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, The Netherlands.
M.Melles@io.tudelft.nl, http://studiolab.io.tudelft.nl/melles
** Dept. of Nursing Affairs, Groningen University Hospital, Groningen, The Netherlands.

Abstract: The aim of our study is to develop design knowledge about contextually based intelligent medical systems used in an intensive care unit. The basic thought is that solutions should be user-driven. This paper describes the premises and outline of our research. A conceptual framework is developed based on Vicente's and Rasmussen's ecological approach for interface design. Constraints posed by the characteristics and task goals of the intensive care nurse and posed by the context will be of main importance. Finally, an outline of the research methods is presented. For eliciting the unique and latent knowledge of the user, we propose a participative ergonomic approach. This approach is embedded in a research-through-design cycle, a method for testing theories in an iterative design cycle, with the underlying assumption that results from experiments can be generalised in the form of design guidelines for future products.

Keywords: intensive care unit, intelligent medical systems, human-product interaction, ecological approach, research through design, participative ergonomics.

Introduction

The nursing process in intensive care units (ICU) is increasingly characterised by a heavy reliance on medical equipment. The variety of equipment is large and innovations appear on the market continuously. Due to these technological developments, the profession of intensive care nursing has changed. Nurses are increasingly required to conduct complex therapeutic and diagnostic procedures using the equipment's advanced functionality. Despite this increased functionality, most (monitoring) devices still function essentially as 'single-sensor-single-indicator' devices (Effken, 1997). The task of selecting and integrating the vast amount of data into diagnostic information is still the responsibility of the nurse. Groen (1995) identified enhanced cognitive demands required by the complex equipment as one of the main stress factors in ICU nursing. On top of this, the usability of the ICU equipment is a contributing factor to human error (Bogner, 1994). Devices are not standardised, and procedures for operating and maintaining the equipment are incomplete or difficult.

But the equipment itself is not the only source of stress. Organisational and process-related factors play a role as well (e.g. Leys, 2001; Groen, 1995). The frequent occurrence of dynamic and complex situations in an ICU, combined with a high level of responsibility towards seriously ill or dying patients and their relatives places the nurse under a lot of pressure. Deciding which actions should be taken is often done under time-critical circumstances. There is a high work pace, and the cumulative work pressure combined with working in shifts results in fatigue. On top of this, there is an increasing demand on medical staff for higher efficiency. In the Netherlands this demand is especially high with a structural shortage of qualified personnel. Groen also mentions the stressing effect of working with inexperienced staff who cannot assume equal responsibility. To minimise inexperience, training is crucial. However, there is a lack of general training for nursing staff in the use of technology as well as adequate, task-specific training (Bogner, 1994). Especially older nurses will suffer from this lack of focus on device usage.

The next generation of ICU equipment should be adaptable to the needs and cognitive limits of ICU staff in relation to the constraints posed by the ICU context. Such devices, containing next generation intelligent software, should be able to adapt to the user (e.g. level of experience, preferences and physical condition) as well as to the environmental situation (e.g. level of illumination, noise and presence of colleagues). Furthermore, these products should be able to provide adaptive embedded support to users when appropriate. Several researchers claim that a successful application of modern technology depends to a large extent on its ability to function as a "team player" with human practitioners (Sarter and Woods, 2000), or, in other words, to collaborate with the user (DeKoven and Keyson, 2000). We will need to know which technological innovations can be sensibly applied and how this should be done.

Unfortunately, the development of applied interface ergonomics, which is required in the design of such devices, has not kept up with the pace of these new technological advances. There are hardly any design guidelines available about how to apply new ICT technologies in a user-centred way. Standard display ergonomics does not suffice to make the necessary changes in the selection and display of diagnostic and monitoring data. A traditional user interface, for example, is in general not dynamic through time and does not anticipate learning curves of individual users. Usually, it does not support multiple users in various times and spaces (e.g. through internet) nor does it recognise user errors or discuss the treatment with the user. It is therefore difficult to substantially increase usability in modern systems by applying traditional user interface design.

Aim of this study: The aim of our study is to determine whether, when, and how contextually based intelligent medical systems enhance the quality of interaction between intensive care nurse and the medical systems used. We aim at finding design knowledge about these systems, which should lead to an improvement of the effectiveness, efficiency, comfort, and safety of the medical care provided in an intensive care unit.

We aim on improving all four factors by increasing the ease with which the user communicates with the medical equipment. Future medical systems should be able to interact with the nurses in a more natural way, and therefore be better adapted to the comprehensive nursing process. Furthermore, these systems should be able to understand and anticipate the tasks and subsequent intentions of the intensive care nurse as well as the infuencing constraints posed by the context of use. Hence, extensive insight into the complete work process of the intensive care nurse is needed, before and during the development of these products.

The research is user-driven. By taking a participative ergonomic approach we actively involve end-users (i.e. intensive care nurses) during all stages of research and development. Collaboration with ICU staff takes place in the form of observations, focusgroup-interviews, and user tests. Besides ICU staff, management and procurements teams will also be included, as they are responsible for the short-term and long-term investments in the ICU environment.

Design knowledge should be the result of this study. This can be in the form of design guidelines, insights into user behaviour and context constraints as well as case studies in which future ICT technology is applied to show possible materialised solutions to present usage problems. These technological directions will be evaluated by the four ergonomic targets mentioned.

Position of the research: ID-StudioLab and Intelligence in Products group: This project is part of the research program of the Intelligence in Products group, one of the participating members of the ID-StudioLab in Industrial Design Engineering at Delft University of Technology. Furthermore, the project is placed in an existing framework of collaboration involving the department of Nursing Affairs at the Groningen University Hospital. The premises of this research can best be described by the three statements that ID-StudioLab is built upon (Hekkert et al, 2000): (1) Breakthroughs and innovative research require an interdisciplinairy approach (e.g. product and interface designers, psychologists, sociologists, computer scientists) ; (2) All research efforts are user-driven. Design research must pay attention to the full experience of the user. This experience not only covers the perceptual-motor and cognitive skills of the user, but draws heavily upon the social, cultural, and technological context in which the interaction with the product takes place; (3) All research efforts are designer-driven, i.e. all projects are carried out by designers or directed towards designers.

This paper describes the conceptual framework and the blueprint of our research methods for the introduction of intelligent systems into the intensive care unit.

Conceptual framework: an ecological approach

To organise our research, a conceptual framework was set up based on literature research and observations of several wards at the University Hospital of Groningen and the University Hospital of Rotterdam, Dijkzigt (i.e. thorax ICU, surgical ICU, neurosurgical ICU, and paediatric ICU). The fundamental idea behind our framework is the ecological approach to interface design as proposed by Vicente and Rasmussen (1992) and Vicente (1995). According to this approach the environment has a strong influence on the actions taken by the operator of a system, that is the characteristics and task goals of the user and his work domain interact, and are studied as a whole. This is different from the traditional organismic approach which tends to minimise the contextual influences and attributes skilled behaviour mostly to mental constructs and cognitive processes. Ecological interface design (EID) is a framework for interface design especially suited for systems involving complex human-machine interaction.

The goal of EID is to make the relevant dynamic work domain constraints visible in the interface. As a result of the influence of the dynamic environment, the actions taken by an operator to reach a specific goal will vary. Making the relevant constraining influences visible to the user should provide the user with a better insight into the state of the system and the contextual situation. For our purposes, this means: Making the relevant constraining influences visible to the intensive care nurse should provide her with a better insight into the condition of the patient as well as the situation of the entire ward (e.g. presence of colleagues, day or night, condition of other patients). As a result, the interface should provide her with the information needed to plan her actions more effectively than current equipment does.

To accomplish a certain task goal the nurse will take different actions depending on the current situation and the characteristics of the nurse (e.g. fatigue, skill level). As a consequence the information required to plan and perform these actions is dependent on both these factors. For routine tasks, like replacing a syringe, in a routine situation, lower-order variables such as the values of individual variables could suffice and could even be highly efficient. For more complex tasks, like evaluation of the prescribed treatment and planning subsequent actions, higher-order variables such as system status, situational status, and relationships between variables could be needed to support the nurse in her diagnosis (Effken, 1997), especially when the situation at the ward is chaotic as well and the nurse has to prioritise her actions. The designer has to determine which of the many constraints and subsystems are relevant and should be present in the interface. Subsequently the designer has to determine how to represent these relationships, and when which form of information is needed and should be available to the user. Hence, an elaborate task analysis is needed in which the different sources of constraints are incorporated. This task analysis results in a description of the current situation and a prescription of future situations. The descriptive task model indicates (among others) which information is used and available in present work situations. The prescriptive model describes (among others) which information should be available in which situation.

The (interface) design of ICU equipment according to the ecological approach starts by identifying the dynamic set of environmental constraints on the behaviour of the intensive care nurse. We identified five sources of work domain constraints which influence the interaction between the nurse and the medical system, namely teamwork, the situation on the ward, other medical personnel, especially clinicians, who are obviously extremely important for the nursing process, and the patient being the biological system to be controlled. Besides functioning as a system, the patient also is a seriously ill human being. The intensive care nurse is the main source of information for the patient, and for the relatives. The patient acts, like the relatives, as a passive user of the equipment as well. Besides these environmental influences, the operator characteristics of the intensive care nurse and her task goals have to be taken into account. These are the sources of constraints which have to be considered in defining the interface of future ICU equipment, and therefore define our conceptual framework as shown in figure 1. In the following, a short description is provided of these (constraining) elements.

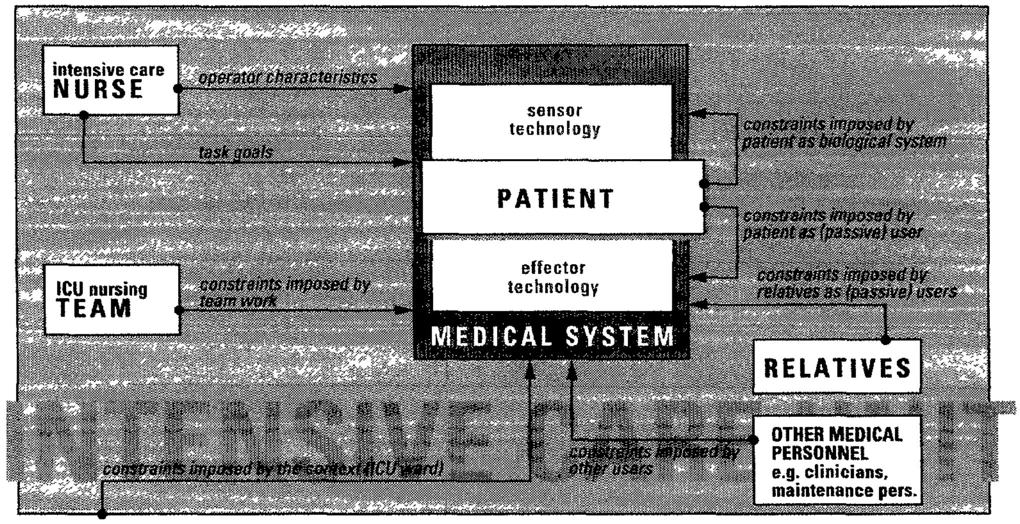

Figure 1 - Conceptual framework

Teamwork and the situation on the ward have a huge influence on the work process of the nurse. The patient is the biological system to be controlled. Besides functioning as a system, the patient also acts, like the relatives, as a passive user of the equipment. Other medical personnel, especially clinicians, are obviously extremely important for the nursing process and therefore must be included.

Medical system: Connected to the patient is the sensor and effector technology. Sensor technology (monitoring equipment) is used to measure and display a number of parameters read from the patient. Some parameters are routinely monitored for every patient (e.g. heart rate, respiration, blood pressure, body temperature, saturation (oxygenation of the blood)). All these measurements can be done either as one-off readings or as a continuous process. Effector technology (treatment or support equipment) is used for interventions to help patients recover from (sudden) changes in their conditional state. The functions that these machines perform range from completely taking over a function of the body to supporting the activity of the patient.

A lack of proper design standards for medical equipment has led to a diversity of interfaces. Bogner (1994) mentions that non-standardisation may be responsible for erroneous actions, as well as incomplete or difficult procedures for operating and maintaining the equipment. Other research confirms much of her findings (e.g. Obradovich & Woods, 1996; Bogner, 1994; Cook et al, 1992).

Groen (1995) concludes that nurses handle the information from the equipment with caution, because they do not always consider it reliable. When the image of the patient is not clear because the information from different sources (i.e. the equipment and the patient) does not converge, the role of the technology is called into question. The information that is observed directly on the patient is judged as more reliable. This set of priorities emphasises that the patient is central to the care process and that the technology is just an aid.

Patient as the biological system to be controlled: The objective of an intensive care unit in general is to control and improve the condition of the patient. In our framework, this implies that in the ICU work domain the patient is the system to be controlled. A patient could be considered as a complex biological system consisting of many highly coupled subsystems. This makes treatment of a patient (i.e. arriving at a diagnosis (problem definition), an etiology (cause or causes), and a prognosis (likely outcome of the possible treatment actions)) extremely difficult. The state of the patient is often unclear, and the precise effects of each treatment are uncertain as well: A certain treatment can solve one problem, but at the same time create a new problem or intensify a problem in another subsystem.

Miller (2000) states that ICU patients are biological systems that operate according to cybernetic rules. Critically ill ICU-patients operate in deranged states that are outside the bounds of homeostasis. This derangement affects their innate biological control system. According to her findings, it is therefore critical that models of ICU patients include and visualise these biological control systems. A user interface should make the underlying structure of the deranged patient visible.

Effkens work (1997) is based on the same premise. She evaluated the ecological approach used in interface design for a haemodynamic monitoring and control task. She also concludes that a patient should be considered as a complex system consisting of many highly coupled subsystems. Her research shows that making the relevant relationships visible in the interface result in a more accurate diagnosis and treatment of clinical problems by experts as well as novices.

Task goals of the intensive care nurse: The nurse's tasks consist of defining and implementing care plans, execution of the treatment as prescribed by the clinician, monitoring of the patient and operating the equipment (cure). The biggest part of the task consists of evaluating medical regulation. The nurse is continuously inspecting the data provided by the equipment as well as the vital signs of the patient to see if everything is normal; whether all the data is ok, and if not, is intervention immediately required, or is there time to consult the clinician.

The main goal of an intensive care nurse is returning the patient to as healthy a state as possible, by bringing the patient in a state of homeostasis and subsequently maintaining this state. Homeostasis is defined as an internal state of dynamic balance. It is reached when all physiological variables are operating within their normal bounds. This embedded nature of control influences the relation between nurse and patient. Miller (2000) describes this very effective: because the core system of the patient follows its own logic, clinicians have to play two roles. Assuming the role of collaborator with processes tending towards homeostasis, and saboteur of processes tending away from homeostasis.

Another important factor in the use of medical equipment related to the intended tasks is that the nurses are responsible not only for the device operation, but also for the larger performance goals of the overall system. As a result, the system of people and artefacts evolve over time to produce generally successful performance, even if the usability of that system is poor. Cook and Woods (1996) call this adaptation "tailoring processes" or "user tailoring".

Characteristics of the intensive care nurse: The characteristics and working methods of the intensive care nurse have been the object of several studies. Differences can be identified in skill level concerning information handling and decision making, and in skill level concerning the use of the equipment.

Benner (1992) has distinguished four levels of practice in critical care nursing, based on the Dreyfus Model of Skill Acquisition, shifting from advanced beginner to expert. In the process of becoming an expert, the learner moves from analytical and rule-based thinking to intuition, and from detachment of the situation to involvement. During this process knowledge becomes embedded in practice and can hardly be separated from that practice. These differences are apparent from the way information is handled and from how much information can be handled by a certain nurse. IC-nursing is characterised by unpredictability. Often there are situations in which there is no standard procedure available (unfamiliar situations as defined by Vicente, 1992). Nurses deal with this by setting priorities on the basis of images they construct, both of the individual patient and of the ward as a whole. An expert nurse is capable of dealing with more information than just that of her own patients. She knows how to prioritise and zooms in on information that needs more attention (Groen, 1995). She hypothesizes and calculates the corresponding probability of occurrence, while at the same time overseeing all the relevant evidence. The beginning nurse can only process a small part of the information provided and only in the order learned (rule-based). All information is seen as having equal importance and there is no insight in prioritising. A beginning nurse concentrates on the so-called evidence, but has difficulty with hypothesizing and calculating possibilities. She has to translate her knowledge in the form of rules to concrete action and these actions are susceptible to human error. In addition, these translations take time, while fast action is needed during emergencies.

There is not only a diversity in experience between nurses in providing care, but also in the level of experience with equipment in general and with the actual devices in use at a certain time (e.g. it might be new on the ward). Not only experience gained by practice is relevant. Age is found to be related to general knowledge on how to operate devices. It has an effect on performance which can not be fully compensated by practice. Older users have more problems when operating devices. They have more serious usability problems if devices react inconsistently or do not provide clear guidance to the user (Freudenthal, 1999). For example older users often have problems in applying the principle of 'spatial organisation' (of menus) (Docampo Rama, 2001). These age dependent performance problems are especially relevant in the intensive care unit where, in general, staff is older.

The intensive care unit: The ICU as a work domain is characterised by predictable as well as unpredictable patterns. Most of the time, the pattern of the work process is according to preset tasks and activities (Leys, 2001); dictated by shifts, schedules, visits by other personnel (e.g. fysio-therapists, clinicians), day and night rhythm and equipment procedures (e.g. change of drugs). However, these patterns can suddenly change due to the unstable and therefore often unpredictable status of most patients. Additionally, the number of patients fluctuates strongly. Sudden peaks disappear as quickly as they started and the routine patterns will be picked up again. Nurses have to deal with this unpredictability and try to solve this by prioritising the information they get (from their own patient and the ward as a whole) and hypothesising the consequences.

ICU nursing team: Team play is an important characteristic of ICU nursing. Usually, nurses are responsible for one or two patients. Nurses assist each other with physically difficult tasks, like turning the patient over. They also watch each others' patients when a nurse has to leave the ward temporally. As a consequence, devices are operated collectively. Another important aspect of team play is the trust and reliance nurses must place in each other. They consult each other in doubtful situations and give assistance in crisis situations. Preferably, medical systems should play a role as a team member as well.

The patient and the relatives (as passive users): The intensive care nurse is the main source of information for the patient and the relatives. According to Yen (2001) research has indicated that reducing stress and reducing feelings of isolation have a positive effect on the patient's sense of well-being. A familiar surrounding is an important aspect of the healing and treatment process and eases the acceptance of serious illness. Providing feedback on the treatment process can help reassure the patient. An interface design based on these patient centred care principles can stimulate these psychological effects (Yen, 2001). The design of most modern healthcare facilities ignores these principles, thereby unintentionally reinforcing the patient's idea of sickness. Naturally, the physical comfort of the patient should also be taken into account.

Research methods

It is clear from the previous discussion that our research is based on a user-driven approach as well as a designer-driven approach. These aspects translate into two empirical research methods, participative ergonomics and research-through-design respectively. Participative ergonomics is an extension to classical ergonomics whereby the end-user is actively involved in the product development process (Vink et al., 2001). This method elicits the unique and often latent knowledge of the user. Research-through-design is a method for testing theories in an iterative design cycle (Hekkert et al, 2000). An underlying assumption of this method is that results from experiments using prototypes can be generalised in the form of design guidelines for future products. To organise our research we use the method of grounded theory as an overarching structure (Strauss & Corbin, 1998). The grounded theory method (a method from the social sciences) aims at developing theories from systematically obtained data. These data are acquired in several rounds in which the resulting hypotheses are evaluated and adapted interactively. Within this grounded theory method, the two empirical methods described will be used for gathering the data. Literature is also perceived as data, which is to be analysed and evaluated. A blueprint of our research methods, is illustrated in figure 2.

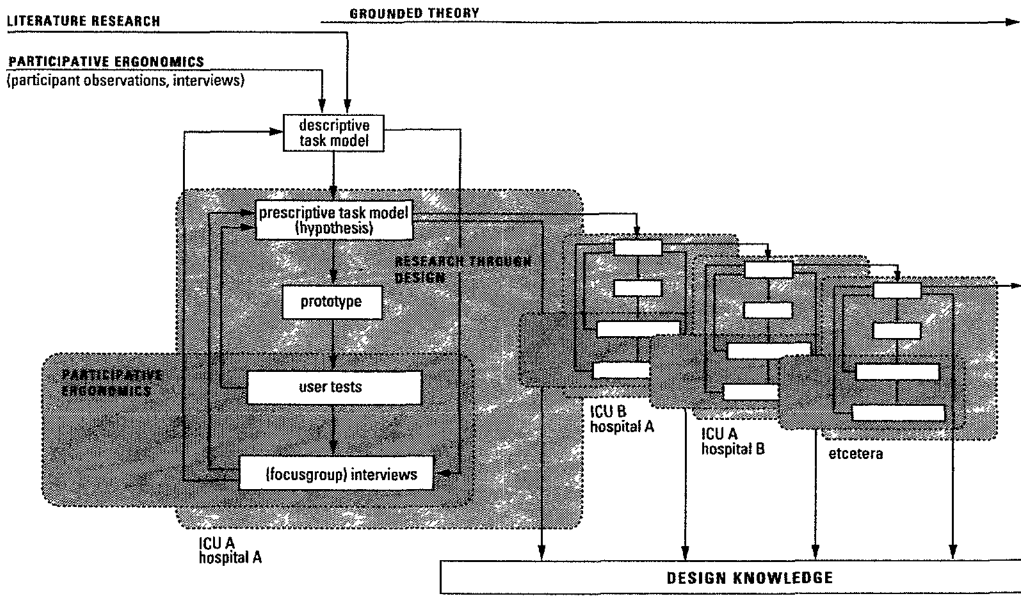

Figure 2 - Method blueprint

The method of grounded theory is the overarching method, the arrow indicating the chronological sequence of several iterations of investigations. Literature research, participative ergonomics and research-through-design are used for gathering data and testing the hypotheses. The research-cycle will be repeated across several ICU's and hospitals.

Taking our conceptual framework as basic principle, we have started with an elaborate task analysis of the nurses' characteristics and their task world. The ecological approach has important implications for the choice of task analysis method, given the emphasis on analysing the environment. The variability in the actions taken by the nurse as a result of the influences from the environment, should be taken into account by the method used. Therefore, the task analysis methodology should provide descriptions of at least the following three classes of constraints (Vicente, 1995): (a) the functional problem space in which the nurses behaviour takes place, (b) the tasks that are to be accomplished by the nurse, and (c) the set of strategies that nurses can use to carry out these tasks. We use Groupware Task Analysis (GTA) and DUTCH (Welie, 2001). The fields of application of these methods is when either the current way of performing tasks is not considered optimal, or the availability of new technology is expected to allow improvement over current methods. Moreover, GTA puts an emphasis on studying a group or organisation and their activities.

We have started with analysing the current task situation resulting in preliminary descriptive models. These descriptive task models will be presented to focus groups of intensive care nurses and according to their reactions adjusted and elaborated. Subsequently, future task situations are envisioned resulting in prescriptive task models. Again, these models will be developed in collaboration with the end-users.
These prescriptive task models (hypotheses) form the basis for initial case studies. Equipment for the ICU will be developed and tested using prototypes developed to such a level that the subjects can actually experience the interaction. The prototype(s) will be tested using participant observations, user testing in real or simulated environments and (focus group) interviews. Results of these tests lead to new design knowledge (theories) or refinement of the research issues (hypotheses). According to the grounded theory method this process will be repeated several times. Investigation will take place across several intensive care units and across multiple hospitals, thereby identifying possible local effects.

The final result of this research should be design knowledge, in the form of design guidelines, insights into user behaviour and context constraints as well as case studies in which future ICT technology is applied to show possible materialised solutions to present usage problems. Hopefully this research will make both product developers as well as hospital staff (i.e. the intensive care nurses, ICU management, and ICU procurements teams) more aware of usability problems in the ICU.

Acknowledgments
The authors thank prof.dr. C.J. Snijders, prof.dr. H. de Ridder and dr. D.V. Keyson for their helpful comments.

References

Benner, P., Tanner, C., Chesla, C. (1992). From beginner to expert: gaining a differentiated clinical world in critical care nursing. Advanced Nursing Science (14)3:13-28.

Bogner, M.S. (1994). Human Error in Medicine, Lawrence Erlbaum Associates, New Jersey.

Cook, R.I., Woods, D.D., Howie, M.B., Horrow, J.C., Gaba, D.M. (1992). Unintentional Delivery of Vasoactive Drugs With an Electromechanical Infusion Device. Journal of Cardiothoraric and Vascular Anesthesia (6)2:238-244.

Docampo Rama, M. (2001). Technology Generations handling complex User Interfaces, PhD thesis, Eindhoven University of Technology, the Netherlands.

DeKoven, E. and Keyson, D.V. (2000). Designing collaboration in consumer products. Proceedings of the Fall 2000 AAAI Symposium.

Effken, J.A., Kim, N.-G. and Shaw, R.E. (1997). Making the constraints visible: testing the ecological approach to interface design. Ergonomics (40)1:1-27.

Freudenthal, A. (1999). The design of home appliances for young and old consumers, PhD thesis, Delft University Press, Delft, The Netherlands.

Groen, M. (1995). Technology, Work and Organisation. A study of the nursing process in intensive care units, PhD thesis, Maastricht Universitaire Pers, Maastricht, the Netherlands.

Hekkert, P.P.M., Keyson, D., Overbeeke, C.J., & Stappers, P.J. (2000). The Delft ID-StudioLab: Research for and through Design. Proceedings of the Symposium on Design Research in the Netherlands:95-103.

Leys, M. (2001). Technologie, organisatie en verpleegkunde op intensive care en neonatologie afdelingen. Verpleegkunde (16)4:197-207.

Miller, A., Sanderson, P. (2000). Modeling "deranged" physiological systems for ICU information system design. Proceedings of the IEA 2000/HFES 2000 Congress:245-248.

Obradovich, J.H. and Woods, D.D. (1996). Users as designers: How People Cope with Poor HCI Design in Computer-Based Medical Devices. Human Factors (38)4:574-592.

Sarter, N.B. and Woods, D.D. (2000) Team Play with a Powerful and Independent Agent: A Full-Mission Simulation Study. Human Factors (42)3:390-402.

Strauss, A. and Corbin, J. (1998). Basics of Qualitative Research. Techniques and Procedures for Developing Grounded Theory, Sage Publications Inc, Thousand Oaks, California.

Vicente, K.J. and Rasmussen, J. (1992). Ecological Interface Design: Theoretical Foundations. IEEE Transactions on Systems, Man, and Cybernetics (22)4:589-606.

Vicente, K.J. (1995). A Few Implications of an Ecological Approach to Human Factors. In J.Flach, P. Hancock, J. Caird and K. Vicente (eds). Global Perspectives on the Ecology of Human-Machine Systems:54-67 Lawrence Erlbaum, Hillsdale, NJ.

Vink, P., Pennock, H., Scheijndel, P. van and Dort, B. van (2001). Verschillende rollen bij het toepassen van participatieve ergonomie. Tijdschrift voor Ergonomie (26)3:19-23.

Welie, M. van (2001). Task-Based User Interface Design, PhD thesis, Vrije Universiteit, Amsterdam, The Netherlands.

Yen, C.C. and Wooley, M.S. (2001). Affective design solutions for Medical Equipment through PCC Principles. Proceedings of The International Conference on Affective Human Factors Design 2001:289-296.