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Understanding infusion administration in the ICU through Distributed Cognition

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ABSTRACT

To understand how healthcare technologies are used in practice and evaluate them, researchers have argued for adopting the theoretical framework of Distributed Cognition (DC). This paper describes the methods and results of a study in which a DC methodology, Distributed Cognition for Teamwork (DiCoT), was applied to study the use of infusion pumps by nurses in an Intensive Care Unit (ICU). Data was gathered through ethnographic observations and interviews. Data analysis consisted of constructing the representational models of DiCoT, focusing on information flows, physical layouts, social structures and artefacts. The findings show that there is significant distribution of cognition in the ICU: socially, among nurses; physically, through the material environment; and through technological artefacts. The DiCoT methodology facilitated the identification of potential improvements that could increase the safety and efficiency of nurses' interactions with infusion technology.

1. Introduction

There is a need to understand how health practitioners use infusion pumps in context, to improve the design of the devices; incidents occasionally occur during infusion administration, that may compromise patient safety, in general wards [1–3] and also in the Intensive Care Unit (ICU) specifically [4,5]. Researchers have called for taking a Distributed Cognition (DC) approach when analyzing human–computer interaction in the healthcare context, because the traditional model of individual cognition does not reflect the nature of healthcare work [6–8]. DC is a theoretical framework that views cognition as distributed among the members of a social group, between internal and external structure, and through time such that earlier events transform later events [9]. Some previous studies of healthcare work were informed by DC [10–16], but the authors found no reported study that applied DC to study the design and use of medical devices. This paper describes the methods and results of a study in which a methodology based on DC theory, Distributed Cognition for Teamwork (DiCoT) [17,18], was applied to study the use of computer-based infusion pumps in the ICU of a London-based teaching hospital. The study aimed to deliver an improved understanding of the situated use of infusion pumps, which could help improve the safety and usability of the devices, while testing the utility and practicality of applying DiCoT to the study of a socio-technical healthcare system such as the ICU. This paper objectively reports on the actual practice observed in the one ICU studied, and highlights potential areas for improvement, without making any value judgements with regards to the hospital staff or infusion pump manufacturers.

2. Background

2.1. The Intensive Care Unit

Malhotra et al. [4] describe the ICU as a unique and dynamic setting where multiple individuals provide physical and emotional support to critically ill patients. They note that, to an outsider, the workflow is difficult to understand and may seem very disorganized, especially with the beeping alarms and flashing displays of medical equipment. The high-risk patients admitted have many medical complications that require intensive monitoring, interventions, and a range of medications to stabilize them. Consulting physicians, attending physicians, and nurses, each possessing specialized and sometimes overlapping knowledge, are all involved in decision making around patient care. A shortage of appropriately qualified staff results in a heavy and stressful workload for existing nurses [19]. In the seemingly chaotic environment, the team works together in a coordinated way and relies on sophisticated patient care technology, such as smart infusion pumps.

2.2. Infusion pumps

An infusion pump is a device that delivers fluids into a patient's body in a controlled manner. It is used to deliver nutrients or medications such as hormones, antibiotics, chemotherapy drugs, and pain relievers. A smart electronic infusion pump is automated

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and equipped with safety features, such as user-alerts that activate when the user sets the pump's parameters outside specified safety limits. Such infusion pumps are heavily used in the ICU and all patients have ongoing infusions, which makes it a rich environment for studying the use of the devices. The volumetric pump delivers drugs to patients from external bags while the syringe pump delivers drugs from syringes attached to the pump. The volumetric pumps and syringe pumps used in the ICU we studied have nearly identical interfaces, have the same device model, and share the same requirements.

Some of the requirements of infusion pumps include reliability, safety, simplicity in handling and maintenance, and easy access [20]. Despite the emphasis on these requirements, and efforts to improve the safety of intravenous infusions in general, it is relatively common for incidents to occur during infusion administration that compromise patient safety [1–3]. Regarding the ICU specifically, intravenous medication errors are frequent [4,5]. Infusion pumps tend to be the final frontier between decision-making and the administration of medication in the ICU; the implications for patient safety are that this administration is the last point at which a medical error could be detected before manifesting as a probable adverse event, and that any errors initiated at this point will impact upon a patient's physiology. There is therefore a clear need to understand how health practitioners use infusion pumps in the context of the ICU and to make recommendations for future improvements to the design of the devices based on such understanding.

2.3. Studies of infusion pumps

To understand how infusion pumps are really used in practice, situated studies are required to look at the messy details of work. Clinicians typically spend more of their cognitive resources dealing with these details than with the medical aspects of problems [21]. One should search for workplace complexities and uncertainties, and investigate how people cope with them, with the aim of exposing strategies and judgments, so that the robustness of these strategies can be assessed. These cognitive elements of work can be discovered only empirically by the study of work in its natural setting [22], through focused and purposive ethnographic evaluation [23]. Moreover, there are strong arguments that medical artefacts can best be understood in the context in which they are used [24]. However, very few field studies have been done due to ethical and privacy issues, and difficulties in getting access to the field [25].

Studies done on the use of infusion pumps in the ICU so far have focused on identifying sources of errors and quantifying their occurrences [5,26], and on evaluating pump interfaces using techniques such as Heuristic Evaluation [27]. The only study found by the authors that focused on understanding how people use the devices in context was the observational study of Carayon et al. [28]. They studied how nurses use three different types of infusion devices in different hospital units, including the ICU. The observational method gave them insights on the tasks actually carried out versus the tasks prescribed, and they identified divergences in practice that were considered to increase risks of failure. This study also employed an observational method, except that the data gathering and analysis were guided by the principles of DC.

2.4. Distributed Cognition

DC is distinguished by two related theoretical principles [9]. The first principle, pertaining to the boundaries of the unit of analysis for cognition, stipulates that cognitive processes should be looked for, irrespective of physical location, on the basis of the functional relationships of elements that participate in the process. Traditional views of cognition, on the other hand, consider the boundaries to be those of individuals. According to DC, a system can reorganize itself to bring subsystems into coordination to achieve different functions. The second principle, concerning the mechanisms that take part in cognitive processes, states that a larger class of events should be looked for, such as the manipulation of external objects and the flow of information representations among actors, on top of looking at the manipulation of symbols inside individual actors. Besides providing extra memory to the same processes that operate on internal memories, the physical environment presents opportunities to reconfigure the distributed cognitive system to take advantage of different combinations of internal and external processes.

When these principles are applied to the observation of human activity, three kinds of distribution of cognition are seen: distribution across the members of a social group, distribution among internal and external (material or environmental) structure, and distribution through time such that the results of earlier events transform later events. Hollan et al. [9] state that, to understand human cognitive potential, and to design effective human–computer interactions, it is essential to grasp the nature of these distributions of process. Building on these principles and their study of emergency medical dispatch, Furniss and Blandford [17] developed DiCoT, a codified method for applying DC to the analysis of socio-technical systems.

2.5. Distributed Cognition for Teamwork (DiCoT)

DiCoT focuses on building models to capture the information flows, physical layouts and artefacts of systems. A High Level Input–Output Model describes the overall goal of the system in terms of its input, system factors determining the processing, and its output. An Information Flow Model describes the information flows among the actors of the system in terms of the *communication channels* used and key flow properties such as *formal* versus *informal communication*, *information transformation*, *information filtering*, *information buffering*, and *decision hubs*. A Physical Layout Model analyzes how physical structures at different levels support communication among actors and facilitate access to artefacts. It also looks at how spatial arrangement supports cognition, based on principles such as *perception*, *naturalness*, *bodily supports*, *horizon of observation* and *situation awareness*. An Artefact Model analyzes how the detailed design, structure and use of artefacts aid actors in their cognitive work.

DiCoT has been applied to analyze safety critical systems such as emergency medical dispatch [17], mobile healthcare work [16], and underground line control [29]. Webb [29] extended DiCoT with two additional models: a Social Structures Model that examines how cognition is socially distributed within the system by looking at the *mapping between social structures and goal structures*, the *sharing of work*, and the *development and retention of knowledge*; a System Evolution Model looks at the evolution of the system over time to understand why work is arranged in a particular way. In this study, data was gathered to build these models for the context of infusion administration in the ICU. In addition, it was found that other activities influenced infusion pump setup and use, so a new System Activity Model was developed to capture these influences.

2.6. Distributed Cognition and healthcare

As mentioned previously, researchers have described the need for taking a DC approach when studying human–computer interaction in the healthcare context. The arguments they give are that the traditional model of individual cognition does not reflect the complex nature of situated decision-making that occurs among groups of individuals in healthcare work [6], and does not account for the fact that healthcare professionals are increasingly sharing knowledge and skills, to cope with rising costs of healthcare and to leverage rapid knowledge growth [7]. Distributed responsibilities allow the team to process large amounts of information and decrease cognitive load on individuals. Additionally, researchers argue that the traditional model mixes up the processing performed by individuals with the processing performed by the larger systems in which work is carried out [8], and has been ineffective in providing usable frameworks for improving system designata broader level of understanding interaction within natural work settings [29]. They claim that DC theory is better suited for both the study of human performance in healthcare and for the design of technologies meant to assist such work [8], and that understanding DC will become critical in the development of effective user interfaces in healthcare systems [30].

DC has been applied as a theoretical framework in healthcare to study: cognitive artifacts [6,10,11]; spatial arrangement of patient records [12]; bottlenecks that can lead to errors in a psychiatric emergency department [13]; information flow breakdown in the context of patient food delivery [14]; and clinical research data collection forms [15]. The DiCoT methodology specifically has been applied to study mobile healthcare work [16]. Despite the promising role that DC can play in improving the design of technologies meant to assist healthcare work, it has as yet not been applied to study the design and use of medical devices, which are often linked to safety incidents due to interaction design issues. Taking a step in this direction, this study focused on understanding the socio-technical system involved in infusion administration in the ICU, with the aim of informing the design of safer and user-friendlier infusion technology.

3. Methods

To understand the situated use of infusion pumps in the ICU, an exploratory methodology was adopted in this study, consisting of an iterative cycle of data gathering and data analysis. Data on the situated use of infusion pumps was collected through ethnographic observations and interviews in the ICU. A data gathering strategy was planned, then subsequently adapted as the study progressed, based on practical challenges and opportunities encountered. Initial observations served as pilots to shape the data gathering strategy and to help build domain knowledge. Data was analyzed by building the representational models of DiCoT. The outcomes of these analyzes guided further data gathering efforts, with the objective of consolidating the representations created.

3.1. Data gathering

The data gathering comprised a total of 12 h of observations and 6 h of interviews done across 12 visits to the ICU, over a period of four weeks. The first author conducted the fieldwork. Around 5 h of observation time were spent observing eight nurses at work, and the remaining 7 h were spent on general observations of activities and physical layouts. Eight nurses, one nurse-in-charge, two senior educator nurses, one medical physicist, one doctor, one healthcare assistant and one cleaner were interviewed. Permission was obtained from the hospital management to do the study, and ethical clearance was obtained from the UCL ethics committee.

3.1.1. Data gathering points

Although an exploratory approach was adopted for the data gathering, a list of data gathering points was prepared to guide the researcher, as it is practically impossible for a single observer to capture everything in a complex environment such as the ICU. Table 1 below describes the data gathering points. The points in the section ''Situated use of infusion pumps'' were derived from the basic aim of this study, while the points in the section ''DiCoT'' were generated based on the principles associated with the DiCoT models.

3.1.2. Observations and interviews

Nurses using infusion pumps in the ICU were approached and asked by the researcher if they could be observed. If a nurse consented, the researcher observed that nurse, paying attention to the points in Table 1. Nurses had very limited availability, and any attention from them was sporadic and non-sustained. Also, it was hard to pre-arrange interviews given the unpredictability of their work; on some occasions nurses agreed to be interviewed but then postponed indefinitely. To cope with this, the researcher conducted ad hoc and intermittent interviews, asking nurses a few questions at the bedside whenever possible. These interviews were different from conventional interviews in that there was not sustained attention from the participants, and they were different from contextual inquiries [31] in that the questions could not be asked during the activity; rather, questions had to be noted down to be asked during opportune moments, which could be minutes or hours later. To make the most of these small pockets of time that nurses would allocate to the researcher, in terms of getting as many questions answered as possible, the researcher maintained a spreadsheet to keep track of all questions, and selected questions from it to ask. The spreadsheet also helped the researcher to cope with the many activities happening in the ICU; attention was given to activities that seemed most relevant to the questions at hand. Some nurses were not comfortable with the researcher being in the line of sight of patients, and in such cases the researcher stood in the bay corridor. Otherwise, the researcher stood at the bedside next to the nurse. While in the bay corridor, the researcher gathered data on general activities and on the environment, and while at the bedside, the researcher gathered data on nurses' interactions with infusion pumps. The high mortality and morbidity of the ICU make it a distressing environment, and therefore the researcher opted for doing many short observations lasting an hour on average, rather than fewer long ones. Since video recording was not possible for privacy reasons, the researcher took extensive notes while observing activity in the ICU and drew sketches of physical layouts. Also, since audio recording of interviews was practically

Table 1
Data gathering points.

Data point	Method of collection
Situated use of infusion pumps	
How do nurses use infusion pumps?	
Interruptions and distractions that occur	– Observations of nurses administering infusions
Difficulties of using the devices	– Interviews of nurses
Strategies to cope with these difficulties	
DiCoT models	
Social structures	– Interview with head nurse – Documents on organisational structure – Observations of interactions among nurses
Information flows	– Observations of nurses administering infusions – Interviews of nurses, doctors and other staff
Physical layout	– Observations of bay/bed layout – Still pictures of bay/bed layout
Artefacts	– Observations of nurses administering infusions

hard, because of their ad hoc and intermittent nature and the location (bedside), the researcher took notes of participants' responses to questions.

3.2. Data analysis

Data was analyzed through the lens of Distributed Cognition, by creating diagrammatical and narrative representations of the DiCoT models.The notes taken during observations and interviews were word-processed and then classified based on the DiCoT models the data corresponded to. Some data could not be classified into the existing DiCoT models, mainly data related to activities outside the scope of infusion administration but potentially influencing infusion administration, and data related to temporal aspects of interactions such as interruptions. These were initially classified into an ''Other'' category, but as their importance and recurrence became apparent, a System Activity Model and a Temporal Resources Model were created to represent them. For each DiCoT model, all the notes associated with it were analyzed to create a narrative and a representational diagram.Unlike the approach described by Furniss and Blandford [17], in which four hierarchies of narrative are created for each model (summary, detail, further notes and issues), a single level of narrative was created and issues were highlighted separately; this approach was found to be more practical for structuring the type of notes that had been taken. For all models, the initial representations guided further data gathering efforts, aimed at refining the representations. The DC principles associated with the DiCoT models were referred to in order to get insights on the strengths and weaknesses of the current setup of infusion administration.

4. Results

The results of the study are presented through the insights that the different DiCoT models delivered.

4.1. High Level Input–Output Model

The High Level Input–Output Model simply summarises the overall function of the system in terms of input, system factors influencing processing, and output. Fig. 1 above indicates the overall function of the ICU, that is to receive patients from other wards who are in a critical state and are in need of intensive monitoring, or patients who need post-anaesthetic care, and to take care of them until their condition is stable enough for them to be returned to normal wards. Resources in the form of medical staff and medical equipment are allocated to patients depending on the level of care required and on the availability of resources, with the aim of maximising the quality and safety of patient care.The ICU studied consists of 5 bays, a bay being a cluster of beds in a separate room, with a total of 36 beds. Each bed has an infusion pump station next to it, and has one or more nurses assigned to it depending on the patient's criticality.

4.2. System Activity Model

The next model elaborates on the activity of infusion administration and describes other activities that potentially influence it. This model is new; the need for it emerged from the complexity of the ICU environment. Many observed phenomena belonged to ''secondary'' activities, which were independent of infusion administration, the ''primary'' activity for this study, but which could influence infusion administration by, for example, changing the physical environment or causing interruptions. The System Activity Model describes all these activities, first at a high level in the form of a consolidated diagram, see Fig. 2 below, and then at a lower level in the form of a summary for each activity. Another level of detail describes the different tasks involved in the primary activity.

4.2.1. Infusion administration

The primary activity, for the scope of this study, is infusion administration. The doctor examines the new ICU patient's file to decide which drugs need to be prescribed, based on inputs from the surgeon and the anaesthetist. The doctor then enters all prescriptions into the Electronic Patient Record (EPR). The nurse prepares and administers the required drugs to the patient. This consists of the following tasks:

1. Reading the prescriptions from the EPR.
2. Calculating the required medication dose and flow rate based on medication information available in the Drug Chart menu of the EPR, taking into consideration patient-specific parameters such as body weight.
3. Preparing the medication at the required concentration, and putting it into the syringe/bag (syringe in case of a syringe driver pump or bag in case of a volumetric pump)
4. Connecting the syringe/bag to the infusion pump and to the patient.
5. Programming the infusion rate, and optionally Volume To Be Infused.
6. Starting the infusion.
7. Recording the volume infused every hour into the EPR and resetting the volume counter.
8. Replacing the syringe/bag with a new one when required. The replacement is usually prepared in advance for a smooth transition.

If the nurse is concerned about the patient's state, he/she contacts the doctor, who examines the patient again. If required, the doctor updates the prescriptions and the nurse changes the infusions accordingly.

4.2.2. Secondary activities

Eight secondary activities were identified as having an influence on infusion administration, as follows.

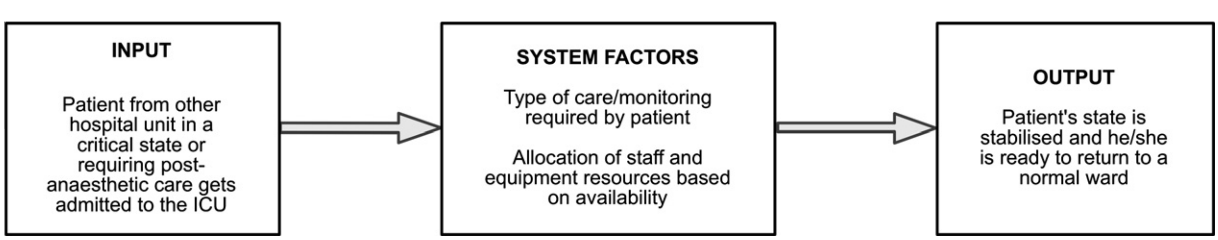

Fig. 1. High Level Input–Output Model of the ICU.

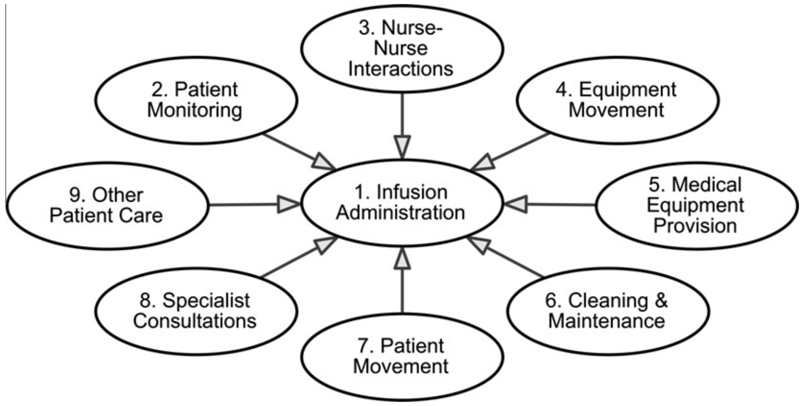

Fig. 2. System Activity Model of the ICU.

4.2.2.1. Patient monitoring. The nurse regularly checks the patient's condition physically and on the life support system. This activity could be interleaved with Infusion Administration, resulting in a multitasking scenario. Also, infusions may need to be modified after certain changes in the patient's condition. For example, when trying to control a patient's blood pressure with an adrenaline infusion, the nurse needs to continuously check the blood pressure and modify the infusion until the desired balance is reached. Lastly, if the life support system alarm goes off while the nurse is preparing an infusion, this will be an interruption.

4.2.2.2. Nurse–nurse interactions. Nurses continuously interact with each other for various reasons, and collaborate significantly. While administering an infusion, a nurse could get interrupted by: another nurse asking for help with something extremely urgent, a senior nurse asking him/her to sign a drug administration sheet, or other nurses stopping by for a friendly chat. Also, the quality of the shift handover determines how well informed the new shift nurse initially is about the state of ongoing infusions.

4.2.2.3. Equipment movement. Medical equipment is continuously moved around in the ICU. It is common for nurses to take idle pumps from other beds, if they cannot easily get a new one from the medical physics stock. This activity influences Infusion Administration by causing changes in the physical layout of the bed area when pumps are displaced.

4.2.2.4. Medical equipment provision. If, for some reason, a pump is not immediately functional, a nurse takes the pump to the medical physics office, and retrieves a spare pump. According to nurses, sometimes they cannot get a replacement from there, and look for spare pumps at other beds. If a pump breaks down while a nurse is using it, it can be a disruptive interruption to Infusion Administration. Then, the ease with which the nurse can find a replacement pump determines how quickly the infusion can be resumed.

4.2.2.5. Cleaning and maintenance. The ICU has very strict hygiene requirements, and the beds and bays are cleaned regularly throughout the day. Cleaners often move artefacts around, causing changes in the physical layout. Consequently, a nurse might need to reconfigure the physical setup before starting infusions.

4.2.2.6. Patient movement. Patients typically stay in the ICU for one night, resulting in high daily patient traffic. Infusion pumps follow patients to other wards if infusions are still required. The displacement of pumps means that the physical layout of the infusion setup at a bed changes.

4.2.2.7. Specialist consultations. Specialists, such as microbiologists and physiotherapists, visit the ICU regularly to check patients or to respond to consultation requests. These consultations can result in communications that change infusion requirements.

4.2.2.8. Other patient care. Patient care also consists of other activities such as the provision of meals. These can change the physical layout or cause interruptions and distractions. For example, a food trolley could hinder a nurse and block line of sight to infusion attachments.

This model gives a structured overview of the many influences that can disturb the activity of infusion administration and the broader use of pumps.

4.3. Social structures model

The social structures model, from the DiCoT adaptation by Webb [29], aims to understand how the social structures of the organisation map onto the goal structures of the system, how work is shared, how robustness is achieved, and how the system learns through the developing knowledge of the actors.

4.3.1. Mapping social structure to goal structure

A hierarchical structure can map to a goal structure such that superordinate and subordinate share responsibility to ensure that sub-goals of the overall goal are satisfied. The diagram in Fig. 3 was developed to represent the sharing of goals for infusion administration across the social hierarchy.

The goal of the Nurse-in-Charge, g1, is to provide nursing care to all patients in all bays of her division. The Nurse-in-Charge and the Bay Coordinator share the sub-goal sg1 of providing nursing care to all patients in a particular bay. The Bay Coordinator is responsible for all patients in a particular bay, and shares the sub-goal sg11 with a Nurse of providing nursing care for a particular bed in the bay.

The Doctor and the Nurse share the sub-goal sg2 of treating the patient with the required drugs and sustaining the patient with life support mechanisms. To treat the patient, a Nurse has individual sub-goals, e.g. sg111, pertaining to activities defined in the System Activity Model, such as Infusion Administration and Patient Monitoring. During the daily shift handover, a nurse is briefed firstly on his/her particular patient, secondly on all patients in his/her bay, and thirdly on all "hot" (extremely critical) patients across the ICU. When a particular patient's assigned nurse is away, or in case of emergency, another nurse could intervene on the patient's infusions. This can be viewed as another sub-goal sg3 shared among all nurses in the bay.

Despite the existence of this formal structure, relationships amongst actors are more web-like. One of the ICU goals displayed on the notice boards in the bays is to make the environment as positive and friendly as possible, to decrease the feelings of morbidity and mortality prevalent in the ICU. Having a social structure where nurses and other clinicians are encouraged to socialise with each other through informal chats helps to achieve this, and at the same time, these informal chats also support the social distribution of cognition.

4.3.2. Sharing of work

Nurses collaborate significantly, share work, and help each other in their tasks. A highly critical patient can have three nurses assigned and working in parallel, with one nurse setting up infusion pumps, another one checking the life support system, and another one updating the patient's record. Admitting a new patient can require extra manpower, in which case nurses request help from colleagues. Help is not necessarily planned beforehand and can be asked for on the spot when required. For example, we observed a nurse come to a bed where a senior nurse was overseeing a trainee nurse prepare an infusion, to ask the senior nurse if she could borrow the trainee nurse shortly after to help to lift something in the other bay. When more than one nurse is explicitly assigned to a critical patient, work needs to be split among the nurses. Even then, nurses willingly take on the tasks of their colleagues: we observed one nurse clean a set of infusion pumps, after which her colleague came back and, positively surprised, exclaimed: "Oh thanks! You did the work for me!"

4.3.3. Achieving system robustness

The social structures existing in the ICU help make the system more robust by propagating information, creating redundancies, and facilitating error prevention. Information is propagated when nurses update each other on the current states of their patients. This information exchange helps nurses possess up to date knowledge about neighbouring patients, allowing them to intervene on their infusions if required, and, coupled with the shift handover described above, results in a redundancy mechanism. Errors are prevented when, while collaborating or interacting socially, nurses share expertise, advise their colleagues, and double-check the task operations of their colleagues. For example, we observed that one nurse was about to start a task with his gloves on, but his colleague reminded him that he still had them on and that it might be better to remove them first. Robustness is also provided through the nurse rota being planned such that there is a mixture of experience levels in each bay. Each bay will have junior nurses, senior nurses and mentors of the junior nurses. Besides providing robustness, this rota also promotes the development of knowledge among nurses.

4.3.4. Development and retention of knowledge

The mixture of experience levels that the nurse rota provides in each bay allows junior nurses to learn from senior ones. Also, the rota mixes nurses from six different arbitrary nurse pools, called nurse lines. This means that a nurse works with many different nurses, creating relationships and promoting knowledge exchange. Nurses are trained on infusion pump use by senior educator nurses, who have in-depth knowledge of the functionalities of the pumps and associated procedures. However, we found that some bay nurses lacked knowledge of pump behavior that resulted in inefficient interactions with pumps. For example, one nurse was not aware that it was possible to start a continuous flow infusion without specifying a "Volume To Be Infused", and a couple of nurses did not know that they could administer bolus amounts on demand without any programming.

Important information, such as a new intravenous line dressing being put in use, is posted on notice boards in the coffee room: the coffee room serves both as a social area and as an area where system information is shared. Another platform for knowledge exchange is staff meetings; problems faced and solutions for them are shared, allowing the actors of the system, and hence the system itself, to learn. While the Social Structures Model includes consideration of longer-term learning and knowledge exchange, there is a need to understand the localized information flows that most directly influence interactions with the device; this is the focus for the Information Flow Model.

4.4. Information Flow Model

This model describes the information flows that exist in the activity of infusion administration, shown in Fig. 4 below, in terms of the communication channels among actors and of key flow properties.

Communication between the doctor and the patient happens face-to-face, when the doctor is assessing a new patient or is examining a particular patient after that patient's condition deteriorates. Communication between the doctor and the current shift nurse happens face-to-face, and also via the EPR. The doctor prescribes drugs in the EPR and the nurse refers to it to know which drugs to administer to the patient. Nurses continuously update the EPR with information on the patient's state, and the doctor can refer to the EPR to get up-to-date information on the patient. Communi-

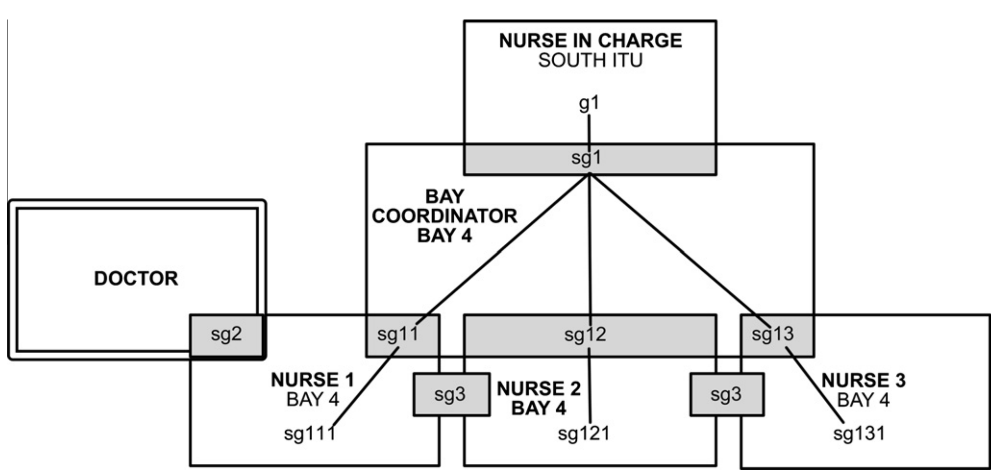

Fig. 3. Goal structure of the ICU. g1 means goal 1 and sg1 means sub-goal 1. sg11 is the child of sg1. Note that sg3 is shared among all nurses.

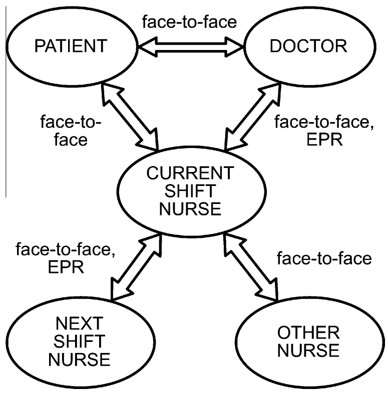

Fig. 4. Information flow for Infusion Administration. EPR stands for Electronic Patient Record.

cation between the nurse and the patient happens face-to-face. While fitting infusion lines, the nurse asks the patient to cooperate with body movements verbally and/or through touch and gestures. Communication between the current shift nurse and the next shift nurse happens face-to-face during shift handover, and also through the EPR, when the current shift nurse accesses information previously entered into the EPR by the previous shift nurse. Communication between the current shift nurse and other nurses, e.g. senior nurses and other bay nurses, happens face-to-face, for administrative formalities, for asking for assistance or for informal chats. During informal chats, nurses often update each other on the states of their patients and propagate information through the system, illustrating the important role that informal communication channels can play.

The doctor acts as an *information decision hub*, taking information from his own examinations, from other specialists, and from nurses, to decide what drugs should be prescribed for the patient. The nurse also acts as an *information decision hub*, taking information about the patient's vital signs from the life support system, and drug-specific information from the computer system, to decide on the drug concentrations that are required to stabilise the patient. Communication among actors and their access to artefacts are influenced by the physical layout of the environment. The next model examines the physical layout of the ICU.

4.5. Physical layout model

The Physical layout model analyzes how the physical environment supports communication among actors and access to artefacts, and how spatial arrangements simplify choice, perception, or internal computation. The physical layout of the ICU was analyzed firstly at the bay level, secondly at the bed level, and finally at the infusion station level.

4.5.1. Bay level

The layout of a typical ICU bay is shown in Fig. 5 below.

The dashed lines represent bed curtains, which by default are open, but can be closed when privacy is desired. This open layout allows nurses to interact with each other easily, and allows other staff passing by to communicate with nurses at bedsides. When the curtains are open, nurses can also see patients at opposite beds, providing *situation awareness* of other patients as well. The office and storage space also serves as an area where nurses and other clinicians congregate for discussions. The notice board is located in the line of sight of incomers. It contains information such as reminders for nurses to label patients' infusion lines with their insertion dates, which is an externalisation of a goal that nurses have while preparing infusions. The open layout of the bay makes it easy for nurses to access artefacts at opposite or adjacent beds if required, helping to make the system robust. For example, we observed one nurse respond to the pump alarm at the opposite bed by going there to switch if off, saying it was a notification that the syringe would be over soon. In essence, the setup facilitates the propagation of information among actors of the system, allows nurses to maintain situation awareness at the level of the bay, and facilitates access to artefacts.

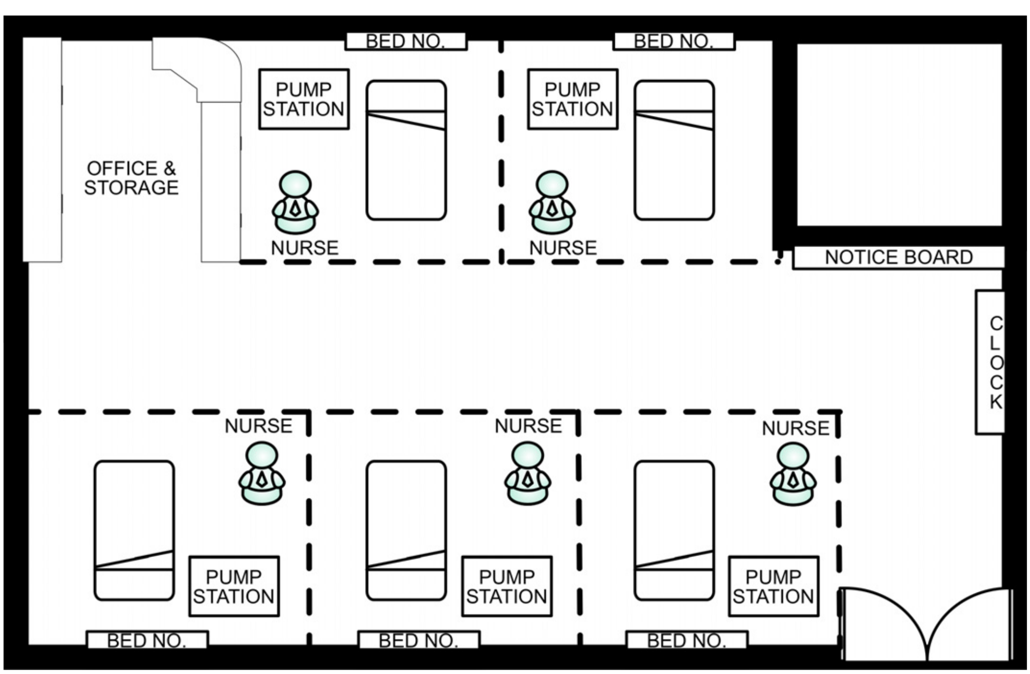

Fig. 5. ICU bay layout.

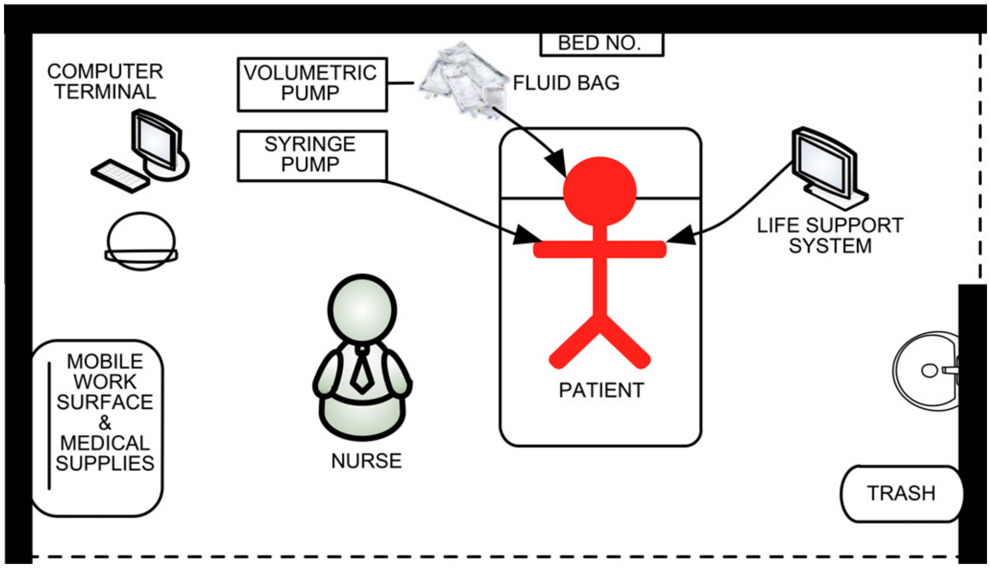

Fig. 6. Typical ICU bed layout.

4.5.2. Bed level

The layout of an ICU bed is typically as shown in Fig. 6 below.

The layout allows several clinicians to be at the bedside at the same time. For example, we observed a nurse, a doctor, and a surgeon collaborate at the bedside after serious deterioration of a patient's condition. The layout also allows a nurse to prepare an infusion, while verbally communicating with the patient and checking the life support system, so that the nurse maintains situation awareness of the patient despite his/her changing visual *horizon of observation*. The horizon of observation is the functional workspace that an actor can monitor in addition to performing a specific task.

The main artefacts used in infusion administration are the medical work surface, the computer terminal and the infusion station. A nurse needs to coordinate information resources represented by these while preparing an infusion, and they are strategically located close together. Additionally, the layout allows all the artefacts to be manned at the same time with, for example, one nurse setting up infusion pumps, another nurse entering data into the EPR, and a third nurse checking the life support readings.

4.5.3. Infusion station level

An infusion station typically consists of two to three active pumps, but in some cases there can be up to eight, adding to the complexity of the setup. The number of pumps in a station changes when pumps accompanying an incoming patient are added, or when pumps accompanying an outgoing patient are removed, or when an inactive pump is taken to another bed.

Nurses externalise information into the environment to facilitate their tasks, and additionally, some physical characteristics of the setup facilitate or hinder the work of nurses, examples of which are given below.

4.5.3.1. Information externalisation. After preparing a medication at the required concentration, a nurse writes a note with the drug name and concentration, and sticks it onto the container. This is to ensure that in the event of an interruption, or if another nurse takes over the task of administering the infusion, the task can be quickly and correctly resumed. Also, after connecting an infusion line to a patient, a nurse sticks a label onto the tube with the drug name and insertion date, to know when the tube needs to be changed. These externalizations of information into the physical environment decrease memory demands of nurses and also help ensure that important information is shared with other shift nurses.

4.5.3.2. Natural mapping. The order of the pumps in the station does not necessarily match the order in which the drugs are prescribed in the EPR, meaning that whenever recording hourly volume intakes, a nurse has to first check which pump is administering the drug. A natural mapping between the order of drugs in the EPR and the order of pumps administering the drugs in the pump station would make this readily perceivable. This mapping can be achieved with the current pump setup; it would need to be incorporated into the nurses' practice.

4.5.3.3. Perception versus Cognition. The line connecting a syringe/bag to a patient is color-coded depending on the type of infusion. For example, epidural anaesthesia lines have yellow attachments. This makes the recognition of the type of infusion a perceptual task. When reading off hourly volume intakes from the syringe driver, nurses sometimes need to position themselves awkwardly or displace the syringe, when the volume label and drug label are as shown in Fig. 7 below. The labeling should be such that both labels are easily perceivable at the same time. From an evolutionary design perspective, this might not be easily achievable due to physical constraints posed by the syringe and its attachment to the pump, but from a revolutionary design perspective, this is a potential area of improvement for future pump design.

This model looked at how the physical environment of the ICU supports cognition and interaction. The final model looks at how artefacts support cognitive work.

Fig. 7. Syringe labeling. The drug label is the yellow paper. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.5.3.4. Artefact model. In this model, the interfaces of the volumetric and syringe pumps were analyzed to understand how they supported or failed to support the cognitive work of nurses.

4.5.3.5. Alarms. The pump has a pre-alarm which gets triggered 10 min before a syringe/bag runs out, to give enough time to prepare an infusion replacement. It reduces the cognitive load of the nurse by externally representing the goal of having to change the syringe soon. The main alarm can be viewed as an information signal that pre-emptively draws the attention of the nurse from other activities to infusion administration.

4.5.3.6. VTBI parameter. When starting an infusion, nurses can specify a Volume To Be Infused (VTBI), which acts as a safety limit. Senior educator nurses discouraged the practice of programming a VTBI for continuous infusions with the syringe driver, following a critical incident: a nurse programmed a volume of 50 ml on a syringe pump, changed the syringe after 45 ml had been dispensed, but then forgot to reprogram the pump to run for another 50 ml; consequently the pump stopped the delivery after dispensing 5 ml from the new syringe. From a DC point of view, the pump should externalise and possibly enforce a goal of reprogramming or confirming the VTBI onto the user after a syringe handling operation is detected; the flow should not be resumed until the nurse explicitly confirms the VTBI.

4.5.3.7. Volume counter reset. Every hour, to record the hourly intake of a drug with the volumetric pump, the nurse needs to access a Status menu from the Main Menu of the pump interface, choose an Intermediate Parameters option, read the volume infused, and then reset the counter to zero. The operation takes 8 key presses. Nurses find this less efficient than doing the same operation with the predecessor pump, which had a physical button for directly resetting running counters. The pump design provides a poor task-action mapping in this particular work context, especially given that this task is performed at an hourly frequency.

5. Discussion

5.1. Distributed Cognition in the ICU socio-technical system

The results of the study portray the ICU as a socio-technical system, in which healthcare practitioners rely on sophisticated technology to achieve the goal of sustaining and treating critical patients. One question this study sought to address was whether DC is particularly well suited as a theoretical framework to study healthcare socio-technical systems, as claimed in the literature, by looking at whether cognition was distributed in the ICU. The findings of this study show that cognition is indeed distributed socially, physically and artefactually in the ICU. The Social Structures Model showed that, firstly, the responsibilities of personnel overlap to ensure that sub-goals of the overall system goal are achieved. Secondly, collaborative problem solving and sharing of work are inherent to the kind of work performed, and different nurses can intervene on an infusion if required. Thirdly, social interactions are highly encouraged to downplay the experience of mortality and morbidity in the ICU, and such interactions influence work. The Physical Layout Model showed that information was externalized into the physical environment, and showed how the physical environment influenced the propagation of information through the system and access to artefacts. The Artefact Model and Information Flow Model showed the important roles that technological artefacts such as the infusion pump and the EPR play in supporting and coordinating activity. The social, physical, and artefactual distribution of cognition that were observed in this study support the claim that DC is well suited as a theoretical framework for analyzing human–computer interactions in a healthcare setting such as the ICU, by explicitly supporting reasoning about cognition that is distributed.

5.2. Strengths of DiCoT in evaluating socio-technical healthcare systems

Another question this study sought to address was, if indeed DC is a suitable theoretical framework for studying a socio-technical system like the ICU, as discussed above, how can it support reasoning and what kind of insights can it lead to, in terms of system design and improvement, when applied through DiCoT. In this study, DiCoT firstly facilitated the description of how the work of infusion administration was carried out in the ICU, providing an understanding of the basic mechanisms involved in the work [32]. Also, DiCoT helped achieve a balance between structure and flexibility – the models and their associated principles guided the data gathering and helped to structure observations, while, at the same time, allowed an open approach by not being prescriptive.

Secondly, through consideration of three types of distribution of cognition, that is social, physical, and artefactual, DiCoT highlighted different types of strengths and weaknesses of the current system setup, based on the principles associated with the DiCoT models. The Social Structures Model showed how the sharing of goals among nurses made the overall system more robust. By considering multiple people in the analysis, DiCoT allows the detection of features of the work that pertain to a cooperative group rather than to a single individual, such as the latter example [33]. The Physical Layout Model analysis at the infusion setup level showed how perceptual principles reduce the cognitive work of nurses (color-coding), and identified improvements in spatial arrangements that could simplify work (position of syringe labels and ordering of pumps).This model also showed how the externalization of information into the environment(bay notice board, medication post-it notes, and infusion line date labels) helps nurses perform their tasks. By explicitly considering the physical environment in the analysis, DiCoT facilitates the understanding of how space is or could be used to reduce the time and memory demands of tasks and to increase the reliability of execution [9]. The analysis of the infusion pump interface done in the Artefact Model showed that the design of the artifact can: reduce cognitive workload (reminder alarms); contribute to safety incidents (VTBI incident); and decrease task efficiency (volume counter reset). By considering artefacts in the analysis, DiCoT supports the understanding of the roles of humans versus artefacts, and the assessment of the consequences of automation, as discussed in the literature [34]. The VTBI incident illustrates the importance of this in the healthcare context: that incident could have been avoided through better design in which the infusion pump forces the user to reconfirm the VTBI after detecting a syringe change operation. The incident also illustrates how DiCoT can help uncover potential safety issues, by looking at the different elements constituting a system – safety has been described as being not a property of individual tasks or actions, but of the interrelationships and interconnections between parts of a system [35].

Thirdly, it is worth highlighting that the ethnographic nature of the data gathering and analysis done through DiCoT yielded insights that could not have been reached through a study which does not consider practice in context. For example, while a Heuristic Evaluation of an infusion pump's interface [27] can result in interesting recommendations for the improvement of the pump's interface, it cannot bring into light design issues that involve the broader context in which the pump is used, since it focuses on the pump's interface in isolation. Some insights of this study could only be derived by understanding practice in context: the issue regarding the ordering of pumps in the station versus the ordering of drugs in the EPR required understanding how both the infusion pumps and the EPR are involved in the workflow of infusion administration; the issue regarding the perception of syringe volume and drug labels required understanding the practice of sticking drug labels onto syringes; the issue regarding the volume counter reset required understanding the practice of checking the volume infused every hour and resetting the running counter; and the VTBI issue required consideration of real scenarios of interactions with the pump. It should be noted that some of these practices are specific to the ICU context.

5.3. Limitation of DiCoT in evaluating socio-technical healthcare systems

One limitation of DiCoT in evaluating a socio-technical healthcare system such as the ICU is the lack of support for analyzing dynamic properties of the physical environment. In this study, it was found that the physical layout of the ICU changes, as infusion pumps are moved around while accompanying patients to other wards or to be used at other beds. To ensure that a pump will be available in case of emergency, given this circulation of pumps, some nurses have devised strategies such as sticking a note on a pump to state that that pump belongs to a particular room or storing a pump in a closet. DC does not support rich analysis about such dynamic properties of the physical environment, and therefore only partially covers the properties of the physical environment that are of interest, as also reported by McKnight and Doherty [16] in their study of mobile healthcare work using DiCoT. Future work should focus on extending DiCoT analysis to better support reasoning about how the dynamism of the physical environment influences cognition.

5.4. Practical considerations of the DC approach

The practical challenges faced while applying DiCoT to the ICU setting were the dependencies on ethnographic data and on domain knowledge. Certain characteristics of the ICU (busyness, privacy, high levels of mortality and morbidity) posed specific constraints to ethnographic data gathering, which limited the type and amount of data collected. Hutchins [22] asserts that applying DC requires a deep understanding of the work domain being studied. In this study, the first two weeks of observations and interviews were spent mostly on building up domain knowledge. Without some minimum understanding of the work domain, it would be hard for an observer to understand pertinent details of the work of nurses. For example, while observing how a nurse deals with interruptions, the researcher needs to know that different types of infusions have different criticalities, and that for some infusions it is alright if there is a few minutes' pause in delivery to the patient, but for some not.

The literature mentions that DC does not provide a pre-defined unit of analysis, admittedly making it harder for new practitioners to apply it, but views this as a potential strength, in that the practitioner can extend the boundary of analysis as required [33,34]. However, in this study, due to the dynamic and variable nature of the ICU setting, it was found necessary to define the scope of the activity that would be studied (infusion administration) more formally with respect to other activities in the ICU. The need for this was compounded by the fact that the open approach to observations generated data for other activities than infusion administration, and these activities seemed to influence infusion administration in some ways. The System Activity Model helped in scoping the unit of analysis, by documenting all observed activities at a high level, before focusing on the main activity being studied. It also created an awareness of inter-activity influences.

6. Conclusion

The goal of this study was to deliver an improved understanding of how nurses interact with computer-based infusion pumps in an ICU, while at the same time testing the practicality and utility of applying DiCoT to this end. Inevitably, as a situated study, findings cannot be generalized to all settings, but highlight some of the local practices that have developed. The nature of the ICU setting posed some constraints to ethnographic data gathering, and the observation and interview techniques had to be adapted to meet these constraints. Data gathering and data analysis were effectively supported by the focus and structure that DiCoT provided through its models and their associated principles. The findings of the study support the claim that DC can be a theoretical framework of choice for studying socio-technical healthcare systems such as the ICU, and show how DC can be applied practically through the DiCoT methodology. Cognition was distributed socially, physically, and artefactually in the activity of infusion administration, and by supporting reasoning about such distribution of cognition, DiCoT facilitated the understanding of some of the strengths of the current system setup and of some potential improvements that could increase the safety and efficiency of nurses' interactions with infusion technology.

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