Journal of Biomedical Informatics 56 (2015) 179–194

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Understanding safety–critical interactions with a home medical device through Distributed Cognition

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ARTICLE INFO

Article history:
Received 8 January 2015
Revised 23 April 2015
Accepted 2 June 2015
Available online 6 June 2015

Keywords:
Distributed Cognition
Home hemodialysis
Ethnography
Safety–critical system
Patient experience
Interaction design

ABSTRACT

As healthcare shifts from the hospital to the home, it is becoming increasingly important to understand how patients interact with home medical devices, to inform the safe and patient-friendly design of these devices. Distributed Cognition (DCog) has been a useful theoretical framework for understanding situated interactions in the healthcare domain. However, it has not previously been applied to study interactions with home medical devices. In this study, DCog was applied to understand renal patients' interactions with Home Hemodialysis Technology (HHT), as an example of a home medical device. Data was gathered through ethnographic observations and interviews with 19 renal patients and interviews with seven professionals. Data was analyzed through the principles summarized in the Distributed Cognition for Teamwork methodology. In this paper we focus on the analysis of system activities, information flows, social structures, physical layouts, and artefacts. By explicitly considering different ways in which cognitive processes are distributed, the DCog approach helped to understand patients' interaction strategies, and pointed to design opportunities that could improve patients' experiences of using HHT. The findings highlight the need to design HHT taking into consideration likely scenarios of use in the home and of the broader home context. A setting such as home hemodialysis has the characteristics of a complex and safety–critical socio-technical system, and a DCog approach effectively helps to understand how safety is achieved or compromised in such a system.

1. Introduction

With the anticipated rise in home healthcare, particularly for chronic conditions [20], there is a need to ensure that home medical devices are designed such that they can be easily and safely used by patients and carers. To inform the design of these devices, it is important to understand how patients and carers currently interact with medical devices in the home environment. Distributed Cognition (DCog) is a theoretical approach that has proven effective for understanding situated interactions in the healthcare domain, in which work is often collaborative, involving both people and technology. However, DCog has not previously been applied to study situated interactions with home medical devices. This study aimed to investigate the utility of DCog for informing the design of home medical devices, taking Home Hemodialysis Technology (HHT) as an example. Through a DCog approach, this study focused on understanding the contexts in which patients interact with HHT, the issues they face, especially those having safety implications, and the interaction strategies they adopt to cope with these issues. The results of the study are presented in terms of five models that describe the contexts in which patients interact with HHT. The next section summarizes the need to understand situated interactions with home medical devices, describes DCog, and gives a background of home hemodialysis.

2. Background

2.1. The need to understand interactions with home medical devices

In many countries, patients are taking more responsibility for their own health management in the home. This is being made possible by advances in medical devices, products and technologies, and the US Food and Drug Administration describes home care systems as the fastest growing segment of the medical device industry [23].

There are a number of challenges associated with the design and use of Home Medical Devices (HMDs) [15,20]. Users of HMDs include people of all ages, and with various disabilities

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http://dx.doi.org/10.1016/j.jbi.2015.06.002
1532-0464/

and impairments. They may not have adequate training in device use, and may be experiencing stress due to being ill. Additionally, the home environment lacks the safety and support systems found in clinical settings, and typically have less space to maneuver medical equipment.

For home healthcare to be a safe and smooth experience, HMDs need to be designed with the requirements and constraints of the home environment in mind [20], and with an understanding of how medical devices are actually used in practice in that environment. To achieve this, interactions between users and HMDs in the real context of use need to be understood, recognizing that people do not always perform tasks as prescribed [5]. Rather, they employ strategies that take advantage of the physical and social environments to optimize their tasks, and develop workarounds to cope with difficulties encountered.

Very few studies have reported on interaction strategies in the context of a medical device being used in the home [32,22]. Lehoux [22] identifies some interaction strategies, but focuses on patients' acceptance of the technologies. Obradovich and Woods [32] also report on strategies, but in their case, community nurses were the primary users of the technology. This study focuses on understanding patients' interaction strategies in the context of home hemodialysis. In a companion paper, based on a thematic analysis of the same data as the study reported here, Rajkomar et al. [36] present findings regarding the use of HHT under headings of learnability, usability and safety; in the discussion section (below), we briefly reflect on the commonalities and differences between the two analyses.

2.2. Distributed Cognition

DCog is an approach to understanding the organization of cognitive systems, which considers the whole system as a cognitive unit, encompassing people and materials in the environment, rather than considering solely the individual's cognition [18]. It is distinguished by two related theoretical principles [17]: that cognitive processes should be identified on the basis of the functional relationships between elements that participate in the process; and that a larger class of events should be looked for, such as the manipulation of external objects and the traffic of representations among actors, as well as the manipulation of representations inside individual actors. As well as being an extra memory resource, 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. [17] state that to design effective human–computer interactions, it is essential to grasp the nature of these distributions of process.

2.2.1. Distributed Cognition in healthcare

Researchers have argued that DCog is well suited both for the study of human performance in healthcare and for the design of technologies meant to assist such work [16,34], because 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 [28]; mixes up the processing performed by individuals with the processing performed by the larger systems in which work is carried out [16]; and has been ineffective in providing usable frameworks for improving system design within natural work settings [33].

DCog has been applied as a guiding theoretical framework in previous research in healthcare to study: the spatial arrangement of patient records [3]; how cognitive artifacts support work in the operating room [28] and the ward [13]; the differences in interpretation of device-related critical events as a function of professional expertise [21]; the role of cognitive artefacts in collaboration [41]; bottlenecks that can lead to errors in a psychiatric emergency department [8]; sign-out sheet use in a surgical intensive care unit [29]; and clinical research data collection forms [27].

2.2.2. Distributed Cognition in the context of home medical devices

The only reported study that refers to DCog in the context of understanding interactions with a home medical device is the observational study of infusion device use in pre-term labor management by Obradovich and Woods [32]. However, Obradovich and Woods [32] only refer to DCog in abstract terms, describing the composition of the home care system as a distributed cognitive system of multiple cooperating human and machine agents; they do not use it explicitly as an analytical tool to examine situated activity. Obradovich and Woods [32] highlight that making technology a team player requires attending to the context in which the device is to be used and designing the distributed system of human and machine agents that manages the activity in question. It is with this perspective that this study investigated renal patients' interactions with HHT, using the Distributed Cognition for Teamwork (DiCoT) framework [11].

2.2.3. Distributed Cognition for Teamwork (DiCoT)

Building on the DCog literature and their study of emergency medical dispatch, Furniss and Blandford [11] developed DiCoT, a method for applying DCog. It focuses on building models to capture the information flows, physical layouts, artefacts, social structures, and evolution of systems.

The Information Flow Model describes how information flows among the actors of the system in terms of the communication channels used and key flow properties such as information transformation and decision hubs. The Physical Layout Model analyses how physical structures at different levels support communication among actors and facilitate access to artefacts. It also looks at how spatial arrangements support cognition, based on principles such as Naturalness and Horizon of Observation. The Artefact Model analyses how the design, structure and use of artefacts aid actors in their cognitive work. Webb [38] extended DiCoT with two additional models: the Social Structures Model looks at the mapping between social structures and goal structures, the sharing of work, and how robustness is achieved; and the Evolutionary Model looks at the evolution of the system over time to understand why work is arranged in a particular way. Additionally, Rajkomar and Blandford [34] developed a System Activity Model to help make sense of the different activities that happen within the system of interest and that contribute to achieving the overall system goal.

Each model has a number of principles associated with it. These principles help to structure the analysis of different forms of Distributed Cognition and provide explanatory power for observed interaction strategies. They also highlight potential problems and improvements, through the implementation of the principles in system design. As an example, the principle of Naturalness in the Physical Layout Model refers to the argument of Norman [30] that "cognition is aided when the form of the representation matches the properties of what it represents".

It is worth making clear the distinction between DCog and DiCoT. DCog is a theoretical framework, while DiCoT is a methodology that applies this theory in a structured way. The structure is provided mainly in terms of different models, e.g. of information flows, physical layouts, and artefacts, and the principles associated with these models. Though researchers have applied DCog in different ways, the differences lie in the *application* of the theory. This study investigates the utility of DCog as a theoretical framework for understanding situated interactions in a setting such as home hemodialysis, and the DiCoT methodology facilitated the application of DCog.

DiCoT has been applied in the healthcare domain to study: mobile healthcare work [25]; infusion pump use in an intensive care unit [34] and in an oncology day care unit [12]; and glucometer use in a ward [13]. Berndt et al. [4] report on the process of learning DiCoT by applying this method to study infusion device use by anesthetists in the operating room. Reflecting on methods for doing studies on technology use in the home in general, some researchers have described the lack of well-developed methods. In response to this, Kaufman et al. [20] propose a semi-structured set of methods for doing usability testing of new products for self-management of health in the home setting, focusing on usability rather than natural use. Others have suggested that methods commonly used for the workplace should form a starting point [26,31]. In the same spirit, DiCoT was applied in this study, to understand the context in which renal patients interact with HHT and identify their interaction strategies and issues.

2.3. Home hemodialysis

Hemodialysis is a treatment for people suffering from kidney failure. Fig. 1 shows the main components in a typical hemodialysis circuit [24]. During treatment, the patient's blood travels through tubes into the dialyzer, which filters out wastes and extra fluids from the blood. Then the cleaned blood is returned to the patient's body. Pressure sensors monitor the pressures of the flow at different points in the circuit, and alarm if a pressure is outside specified safety limits. An air detector checks for air bubbles and alarms if air bubbles are detected in the cleaned blood flowing back to the patient. Some machines have a pump to inject anti-coagulant into the circuit.

The treatment can be done by a nurse in a hospital or satellite dialysis unit, or by a patient or carer in a satellite unit or at home. The treatment is complex, and consists of many steps, summarized below. During dialysis, the patient is usually confined to a reclining chair or couch, or their bed.

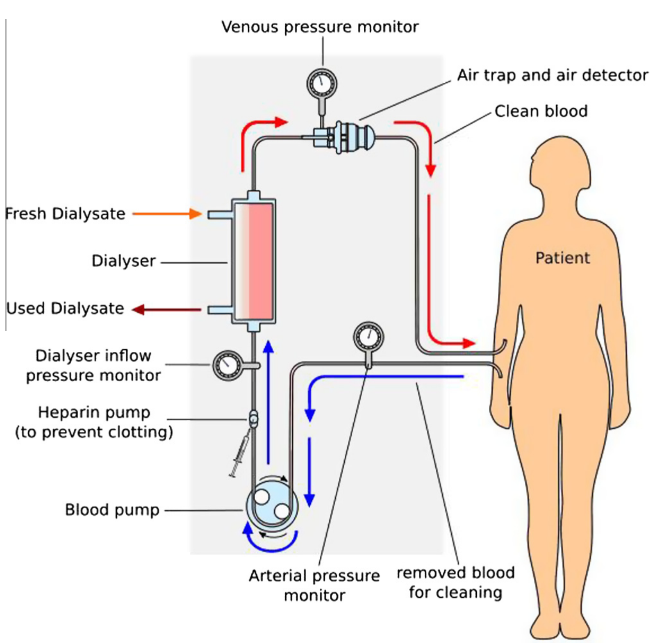


Fig. 1. A hemodialysis circuit. *Source:* MAA Medicare Kidney Charity Fund, Malaysia, n.d.

Home hemodialysis is an invasive, safety–critical treatment. There are inherent risks of patient harm during dialysis that need to be mitigated. Moreover, the many treatment steps need to be performed correctly and in the right order for treatment to be safe.

Previous reported studies that considered human factors in home hemodialysis have focused on the adoption of nocturnal home hemodialysis [39,6,7]. As noted above, Rajkomar et al. [36] report on learnability, usability and safety of HHT. However, no reported study has focused on capturing the contexts in which patients interact with HHT and on understanding their strategies and issues during interactions. This is the focus of the work reported here.

In the home hemodialysis settings reported in this paper, a patient or carer who is eligible for self managing at home is trained in a dialysis unit by nurses. When they are ready, the machine is installed in their home by specialist technicians, and they commence treatment at home. They receive ongoing support from nurses for treatment-related issues and from technicians for technology-related issues. This forms a distributed cognitive system as described below.

3. Methods

Data was gathered through ethnographic observations and interviews with patients and their carers. Patients were under the care of four different hospitals in the UK (H1–H4 in Table 1), and were invited to participate in the study by hospital staff. 19 patients participated in all, and they used 5 different home hemodialysis machines among them (M1–M5 in Table 1). Also, 3 home nurses, 3 renal technicians, and 1 nephrologist were interviewed. Ethical clearance was obtained from a UK National Health Service Research Ethics Committee (reference no. 11/LO/0329). Table 1 gives an overview of the patients' backgrounds. Participants are referred to by fictitious names. A carer is someone who has received some training on caring for the patient; their involvement can vary from only intervening when help is needed, to helping the patient with the needling at the beginning and end of treatment, to setting up the machine and programming the treatment. A helper is someone who has not received training, but occasionally helps with some aspect of the treatment, e.g. handing items to the patient when required, starting the disinfection process on the machine, or intervening in case of emergency. Time 'On Dialysis' and time 'On HH' (Home Hemodialysis) are given up to the date of the first visit to the patient.

During a visit to a patient, the patient was observed during their dialysis treatment, and then interviewed on how they did their treatment. The extent of the observation varied across participants, depending on what the participant was comfortable with, and on average lasted an hour. In some cases the observation covered the patient's preparation for dialysis, the setting up of the machine, and the initial part of the treatment, while in others the observation covered the last part of the treatment and treatment termination. This variation was mostly due to scheduling constraints and to patients having different preferences for when to be observed. Although this variation was incidental, it meant that the study effectively covered the different phases of haemodialysis treatment, which typically lasts 6 h. Each interview was semi-structured and served two main purposes. Firstly, it aimed to understand the patient's background, their current dialysis regime, the activities they perform on a dialysis day, how they felt about their dialysis machine (e.g. whether they viewed it as a friend or as a monster) and about having it in the home, and the

Table 1
Background of participants.

Name	Gender	Age	Carer	Helper	Other conditions	Lives with	On Dialysis	On HH	Hospital	Machine
Adam	M	38	–	Wife	Diabetes	Wife, Son	3 yrs	4 wks	H1	M1
Bob	M	77	Son	Wife	Heart disease	Wife	1 yr	3 wks	H1	M1
Eric	M	72	Wife	–	Paraplegic, diabetic	Wife, 2 Sons	2.5 yrs	3 mts	H1	M1
Fiona	F	26	–	–	–	–	13 yrs	1.5 yrs	H1	M2
Gina	F	65	–	–	–	–	15 yrs	10 yrs	H1	M2
Ivan	M	77	–	Wife	Heart attack, has pacemaker	Wife	8 yrs	3 wks	H1	M1
Jill	F	47	–	Mother	Arthritis	Parents	27 yrs	10 yrs	H1	M2
Alice	F	37	–	Partner, Daughter	–	Partner, Daughter	17 yrs	1.5 yrs	H2	M3
Alex	M	72	Wife	–	Ileostomy, lame, heart attack, prostate problems, parathyroid problems	Wife	2.5 yrs	2 yrs	H3	M4
Bea	F	63	Husband	–	–	Husband	4.5 yrs	3 yrs	H3	M4
Erica	F	64	Husband	–	Diabetes	Husband	No info	9 mts	H3	M5
Felix	M	56	–	Wife	–	Wife	3 yrs	1.5 yrs	H3	M4
Garry	M	43	Wife	–	Hernia problem	Wife	2.5 yrs	1.5 yrs	H3	M3
Ida	F	54	Husband	–	–	Husband	1 yr	1 yr	H3	M3
Jim	M	65	Wife	–	–	Wife, Daughter	4 yrs	2 yrs	H3	M5
Kevin	M	24	–	Mother	–	Parents	3 yrs	2 yrs	H3	M3
Abi	F	41	–	Mother	Impaired vision	–	18 yrs	8.5 yrs	H4	M5
Beth	F	Late 60s	Husband	–	Prosthetic leg	Husband	35 yrs	30 yrs	H4	M5
Eva	F	67	Son	Daughter-in-law	Diabetes, impaired vision	Husband, Son, Daughter-in-law	6 yrs	1 mt	H4	M5

physical and social contexts in which the patient conducted their dialysis. Secondly, through the critical incident technique [10], the interview aimed to elicit incidents and near misses that patients and carers had had, the issues they faced when interacting with home hemodialysis technology, and their strategies for coping with these issues. Data was collected in the form of field notes, audio-recorded interviews and, with the participant's permission, still pictures of the physical environment in which they dialyze and of artefacts that they use.

The observation notes, interview transcripts and pictures were analyzed to construct the representational models of DiCoT, to capture the context in which patients interact with HHT and to identify patients' interaction strategies and issues. This was done by coding data in ATLAS.ti [2] with the DCog principles summarized in DiCoT, through the following steps:

1. Codes were created in ATLAS.ti for the existing DiCoT principles. The interview transcript and observation notes for a particular participant were coded for phenomena that were related to the DiCoT principles. Codes were also created for more general issues and incidents related to a DiCoT model. A snapshot of the ATLAS.ti codes showing the codes for the Information Flow model and the Artefact model is given in Fig. 2, and an example of a coded interview transcript is given in Fig. 3.
2. At the end of the coding process, a document containing all the quotations (coded sections of a document) for that participant was generated. Then, each quotation in the quotation document was paraphrased in an analysis document that was structured hierarchically in terms of: DiCoT model → DiCoT principle → Participant. The purpose of this document was to group insights for a particular principle across all participants. Fig. 4 shows an example of a quotation in a quotation document, and Fig. 5 shows how that quotation has been paraphrased and categorised in the analysis document.
3. Any still pictures that were taken for this participant were analyzed, and any insights were noted in the analysis document.
4. At the end of the study, when the above analysis was completed for all participants, the contents for each DiCoT principle in the analysis document were analyzed, to identify interaction strategies and issues for each principle, across all participants. In all 264 different interaction strategies and issues were identified.

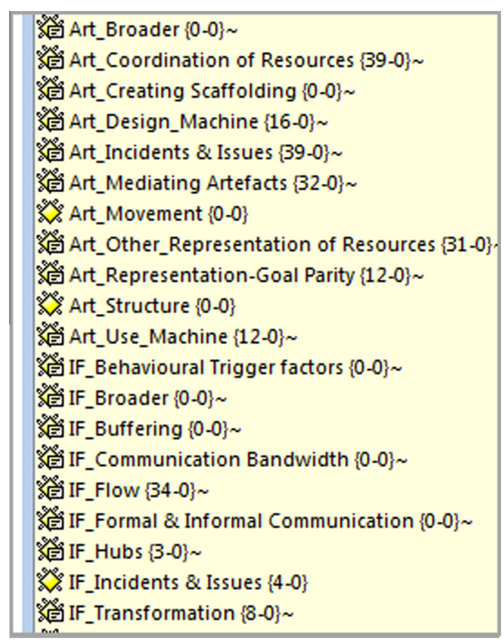
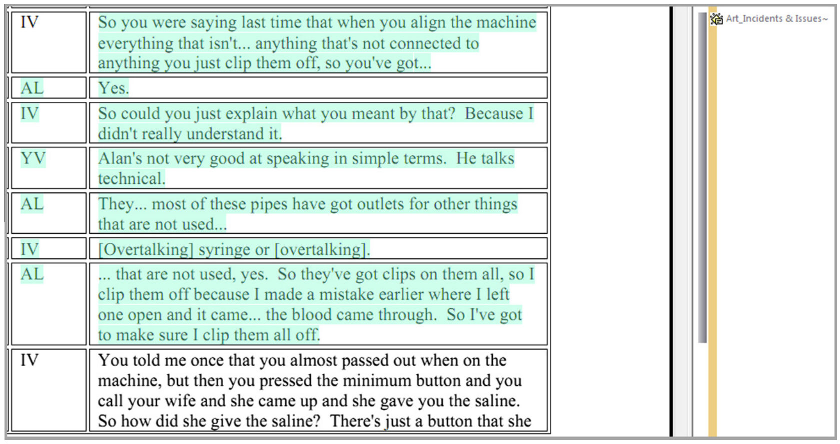


Fig. 2. ATLAS.ti codes for Information Flow model and Artefact model (IF: Information Flow, Art: Artefact).

This paper focuses on presenting the contexts in which patients interact with HHT and some of the main interaction strategies and issues identified in the study, particularly those with safety implications. Inevitably, the models presented are abstracted because they highlight generalizations across 19 participants, omitting the details that pertain to any one individual. It would be possible to develop detailed instantiated models of each study setting (i.e. participant – machine – hospital system), but our aim in this study was to test whether it was possible to produce a single generalized set of models that supports understanding of the use of HHT.

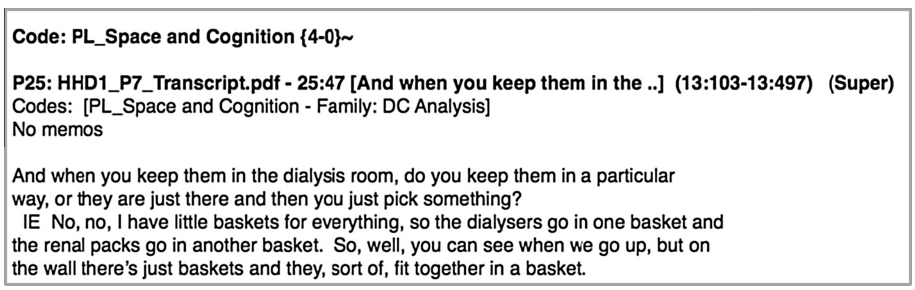
4. Results

The results of the study are presented in terms of the different DiCoT models. As noted above, these are abstract descriptions that



IV	So you were saying last time that when you align the machine everything that isn't... anything that's not connected to anything you just clip them off, so you've got...	
AL	Yes.	
IV	So could you just explain what you meant by that? Because I didn't really understand it.	
YV	Alan's not very good at speaking in simple terms. He talks technical.	
AL	They... most of these pipes have got outlets for other things that are not used...	
IV	[Overtalking] syringe or [overtalking].	
AL	... that are not used, yes. So they've got clips on them all, so I clip them off because I made a mistake earlier where I left one open and it came... the blood came through. So I've got to make sure I clip them all off.	
IV	You told me once that you almost passed out when on the machine, but then you pressed the minimum button and you call your wife and she came up and she gave you the saline. So how did she give the saline? There's just a button that she	

Fig. 3. Example of coded transcript. The section highlighted in green has been coded with 'Art_Incidents & Issues' (Art: Artefact).

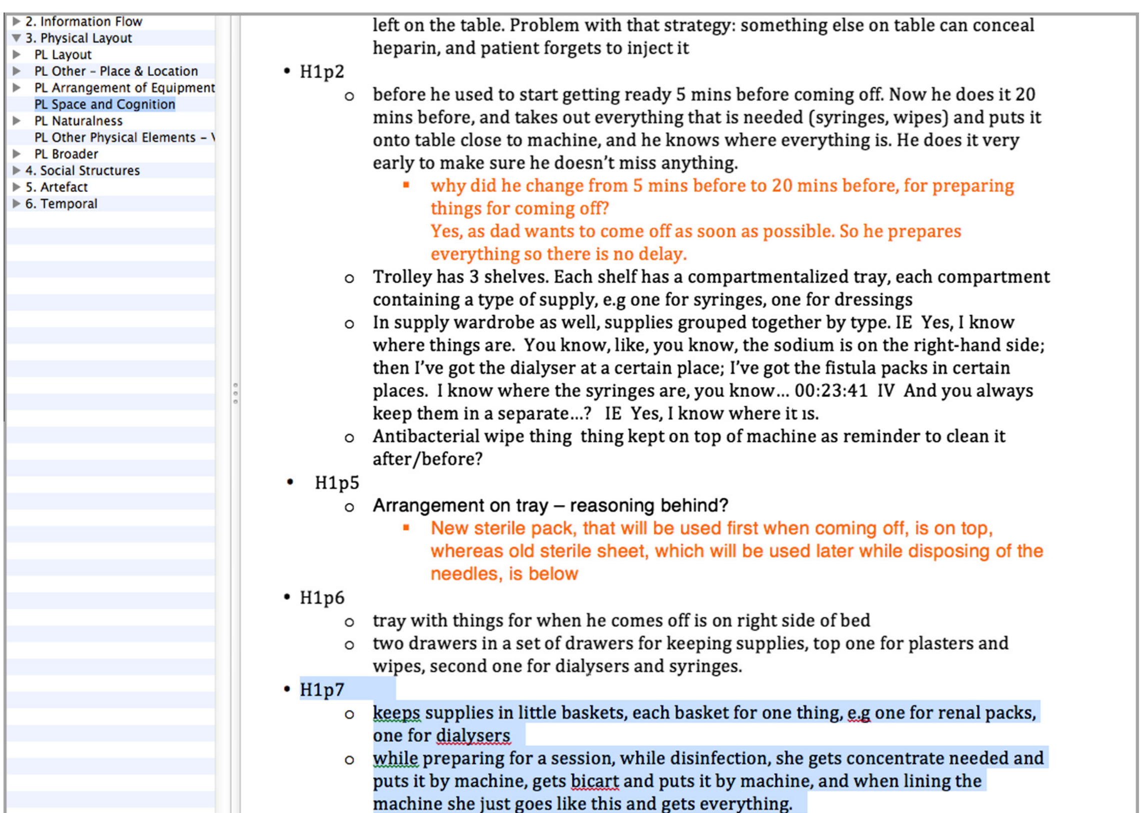


Code: PL_Space and Cognition {4-0}~

P25: HHD1_P7_Transcript.pdf - 25:47 [And when you keep them in the ..] (13:103-13:497) (Super)
Codes: [PL_Space and Cognition - Family: DC Analysis]
No memos

And when you keep them in the dialysis room, do you keep them in a particular way, or they are just there and then you just pick something?
IE No, no, I have little baskets for everything, so the dialysers go in one basket and the renal packs go in another basket. So, well, you can see when we go up, but on the wall there's just baskets and they, sort of, fit together in a basket.

Fig. 4. Example of quotation, coded with 'PL_Space and Cognition' (PL: Physical Layout).



left on the table. Problem with that strategy: something else on table can conceal heparin, and patient forgets to inject it

- H1p2
  - before he used to start getting ready 5 mins before coming off. Now he does it 20 mins before, and takes out everything that is needed (syringes, wipes) and puts it onto table close to machine, and he knows where everything is. He does it very early to make sure he doesn't miss anything.
    - why did he change from 5 mins before to 20 mins before, for preparing things for coming off?
      Yes, as dad wants to come off as soon as possible. So he prepares everything so there is no delay.
  - Trolley has 3 shelves. Each shelf has a compartmentalized tray, each compartment containing a type of supply, e.g one for syringes, one for dressings
  - In supply wardrobe as well, supplies grouped together by type. IE Yes, I know where things are. You know, like, you know, the sodium is on the right-hand side; then I've got the dialyser at a certain place; I've got the fistula packs in certain places. I know where the syringes are, you know... 00:23:41 IV And you always keep them in a separate...? IE Yes, I know where it is.
  - Antibacterial wipe thing thing kept on top of machine as reminder to clean it after/before?
- H1p5
  - Arrangement on tray – reasoning behind?
    - New sterile pack, that will be used first when coming off, is on top, whereas old sterile sheet, which will be used later while disposing of the needles, is below
- H1p6
  - tray with things for when he comes off is on right side of bed
  - two drawers in a set of drawers for keeping supplies, top one for plasters and wipes, second one for dialysers and syringes.
- H1p7
  - keeps supplies in little baskets, each basket for one thing, e.g one for renal packs, one for dialysers
  - while preparing for a session, while disinfection, she gets concentrate needed and puts it by machine, gets bicart and puts it by machine, and when lining the machine she just goes like this and gets everything.

Fig. 5. Quotation shown in Fig. 4 paraphrased and categorised in analysis document (highlighted text). 'H1p7' refers to the participant number. The left pane lists the DiCoT models and the principles associated with each model (only the principles for the Physical Layout model are shown in this figure).

generalize across a diverse set of situations, and they are based on observations as well as verbal data, so it has not always been possible to show the direct derivation of the models from the data in a succinct way. In each model, first a description of the context in which patients typically interact with HHT is given, and then patients' interaction strategies and issues are presented through the different principles associated with that particular model. The temporal structures model has been published previously [35], and the evolution of system design did not emerge as a strong theme in this analysis, so these two models are omitted from the results and discussion. This paper focuses on presenting the interaction strategies and issues that have potential safety implications.

The results show how a DCog approach can help to understand: the basic mechanisms involved in the functioning of a self-care system such as home hemodialysis; the context in which patients interact with HHT; and the interaction strategies and issues of patients.

4.1. System activities

The System Activity model [34] gives an overview of the different activities happening within a system, before the other models give details. However, the context of home hemodialysis is made up of several systems. Therefore, first these systems are defined, and then the activities within the main system of interest, the Home Hemodialysis System, are defined, and finally the tasks within the main activity of interest, the Dialysis activity, are presented.

4.1.1. Systems constituting the home hemodialysis context

5 systems representing the home hemodialysis context were identified, as shown in Fig. 6. These systems are differentiated from each other by the functions for which they exist, as summarized in Table 2.

4.1.2. Activities within the HHS

Within the Home Hemodialysis System, 9 activities were identified, shown in Fig. 7 and summarized in Table 3. These activities each achieve a sub-goal of the overall system goal of providing renal replacement therapy to a patient. The Dialysis activity, the focus of this study, is expanded and shows the actors involved in it. To perform the Dialysis activity, the patient uses the TS and other artefacts.

4.1.3. Tasks within the dialysis activity

The principal tasks in the Dialysis activity are shown in Fig. 8. The tasks and their order vary, depending on the machine a particular patient uses, their hospital's policies, and their own preferences. The tasks represented here do not include troubleshooting and emergency management, which are the steps people need to take to bring the system back to stability.

This model gives an overview of the context of home hemodialysis in terms of the systems, activities and tasks involved. The following models each focus on one aspect of the Dialysis activity, and present the main safety-related interaction strategies and issues identified.

4.2. Information flows

The Information Flow model [11] describes the information flows among the actors of a system in terms of the communication channels used and key flow properties. Furniss and Blandford [11] define three viewpoints for the information flow: a high level input–output view, an agent-based view, and a view focusing on key flow properties. In this study, this model helps to understand the context in which patients interact with HHT in terms of the information processes involved, and to identify related interaction strategies and issues.

4.2.1. High level input–output view for the dialysis activity

The high level input–output view of information flow summarizes input into the system, the system factors and resources that

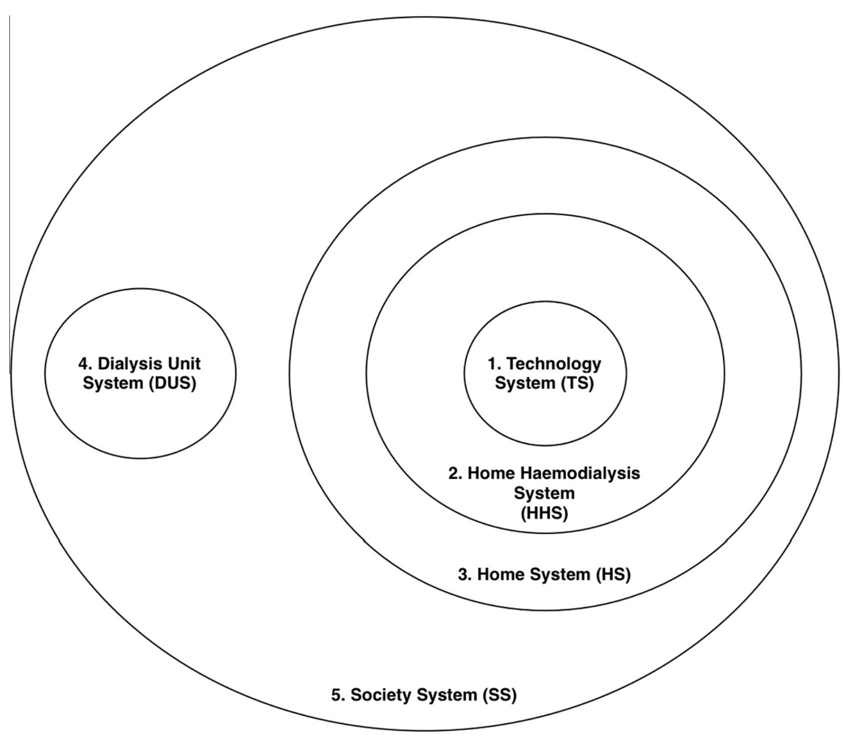


Fig. 6. The context of home hemodialysis in terms of different systems.

Table 2
Description of the systems constituting the home hemodialysis context.

System	Summary
1. Technology System (TS)	This system exists specifically to provide dialysis treatment to the renal patient via the machine, i.e. to clean the patient's blood and remove excess fluid. It consists of the home hemodialysis machine and other technical components such as the water purifier and the water softener. It is a sub-system of the HHS
2. Home Hemodialysis System (HHS)	This system exists specifically to provide renal replacement therapy. It consists of the TS, and other actors and artefacts. The HHS can be seen as a sub-system of the HS, as most of it exists physically within the HS
3. Home System (HS)	This system provides a place of residence to a family, including providing the physical and social environment required for the family to perform a number of activities
4. Dialysis Unit System (DUS)	This system exists to provide hemodialysis treatment to patients who visit the unit, and also to provide support to home hemodialysis patients when required
5. Society System (SS)	This all-encompassing system consists of the HS, the DUS, and, importantly, for the analysis in this study, other patients and other clinical staff belonging to other hospitals and dialysis units

relate to the processing done by the system, and what the system outputs. In the case of the Dialysis activity, the input to the activity is a patient whose blood needs to be cleaned, and the output from the activity is a patient whose blood has been cleaned safely. The resources used to achieve this are human resources, i.e. the actors involved in the activity, the TS, and other artefacts.

4.2.2. Agent-based view of information flow for the dialysis activity

The agent-based view focuses on the principal agents within the system and the flows between them, in terms of the main communication channels. Fig. 9 shows this view for the Dialysis activity. The dotted box shows the patient, the carer, and the helper as one unit, since the other agents may interact with any one of them. Also, the nephrologist is shown in a lighter shade, as the nephrologist is not directly involved *during* the Dialysis activity. The role of each agent during the Dialysis activity is described in Table 4 and each communication process and the main channels used are presented in Table 5. The exact roles of the agents and the flow processes vary across the different hospitals of the study; what is presented here is an abstraction across them.

Table 3
Description of the activities within the Home Hemodialysis System.

Activity	Summary
2.1. Dialysis	This study focuses on this activity, which consists of using the machine in dialysis sessions to clean the patient's blood and remove excess fluids. The main actors in this activity are: the patient, the carer or helper if applicable, the nephrologist, the home nurse and the technician. To perform dialysis, the patient uses the TS and other artefacts (e.g. weighing machine, dialysis chart)
2.2. Monitoring Renal Disease	The patient needs to continuously monitor their health, and, depending on how they feel and the symptoms being experienced, they may need to adjust their dialysis treatment accordingly
2.3. Coordination with Clinical Staff	The patient has to coordinate with the nurse and nephrologist on a regular basis to review the treatment and make required adjustments to the dialysis prescription, medications, or diet
2.4. Medication Management	Renal patients typically need to take several drugs and supplements. The intake of these different drugs needs to be managed by the patient
2.5. Coping with Other Conditions	Some renal patients also have other conditions, which they need to deal with and which may also influence how their dialysis treatment is done, e.g. cardiovascular conditions and diabetes
2.6. Lifestyle Management	Based on a patient's particular condition, that patient has to follow a certain diet, to provide deficient nutrients and counter some effects of dialysis, and carefully manage fluid intake
2.7. Infection Control & Disposal	Before and after dialysis, the dialysis machine needs to be disinfected through a built-in disinfection operation. Also, the patient needs to maintain a high level of hygiene in the dialysis room to prevent infections
2.8. Stock Management	The stock of medical and dialysis supplies that is kept in the patient's home, which consists of many different items and is physically bulky, needs to be managed
2.9. Technical Maintenance	This refers to the technical maintenance of the dialysis machine and other technical components. Some of it can be done by the patient, e.g. changing the water filter in the machine, and some of it is done at regular intervals by the technician

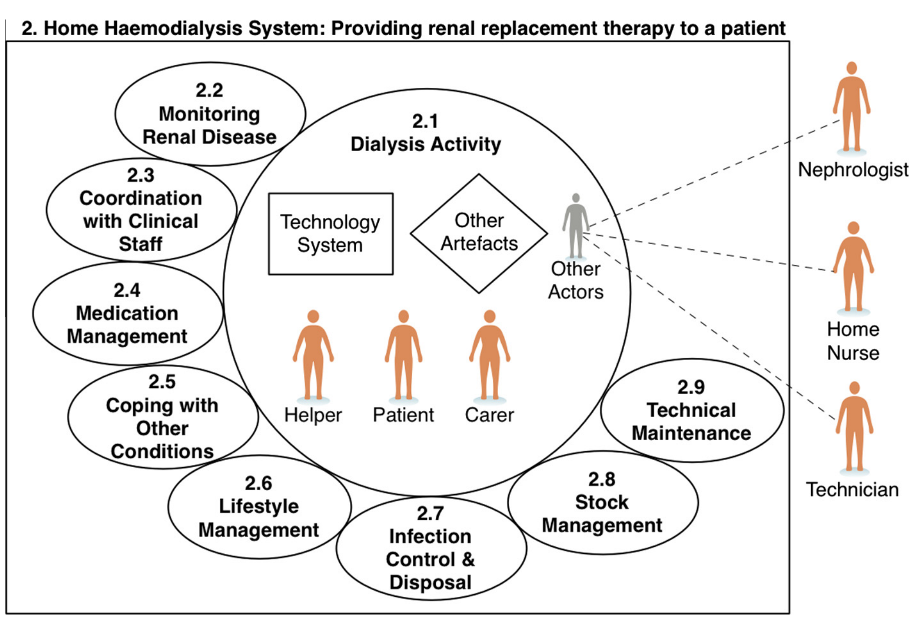


Fig. 7. The activities in the HHS, with the Dialysis activity expanded.

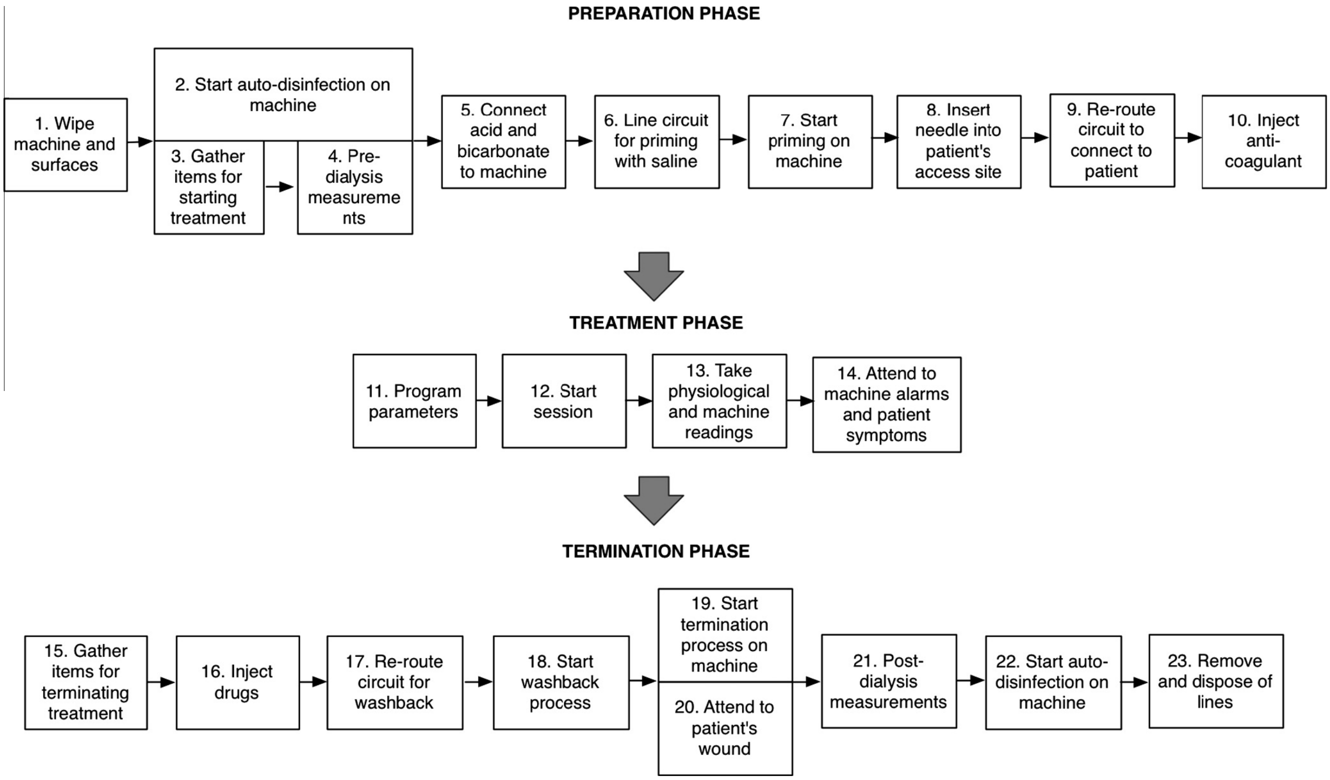


Fig. 8. Principal tasks in the Dialysis activity.

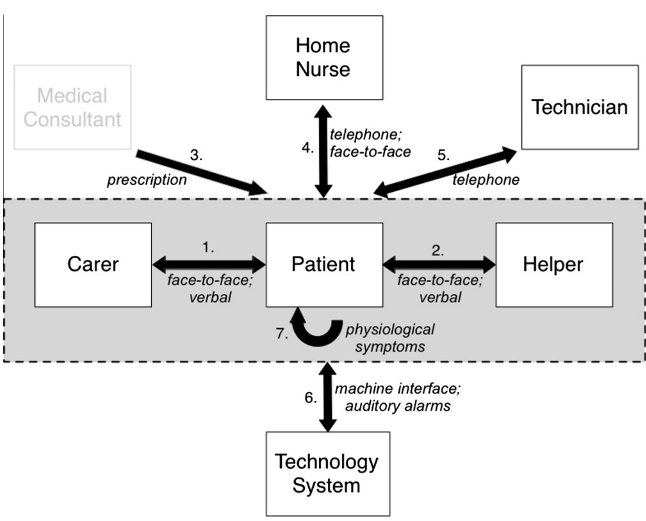


Fig. 9. Agent-based view of information flow during Dialysis activity, showing communication channels.

Table 4
Description of the roles of the agents involved during the Dialysis activity.

Agent	Role
Patient	The patient receives the dialysis treatment through the machine. A self-caring patient conducts their treatment themselves, including the operation of the dialysis machine
Carer	Some patients have a carer who conducts the treatment for the patient, including the operation of the dialysis machine
Helper	A patient may have a helper, who helps the patient with some aspects of the treatment, possibly including interactions with the machine
Nephrologist	The nephrologist sets the dialysis prescription for the patient; the patient programs the dialysis session based on the prescription
Home Nurse	The home nurse provides support to the patient for patient-related issues and machine-related handling issues that arise during dialysis
Technician	The technician provides support to the patient for machine-related technical issues that arise during dialysis
Technology System	The TS is described in Table 2

Several patients introduced an extra communication channel between them and their carer (Process 1), so that they can stay in touch with their carer while their carer is engaged in a HS activity elsewhere in the home. Examples of this communication channel are an intercom system from the patient's dialysis site to the kitchen, a pair of walkie-talkies, or a buzzer and alarm set (e.g., Fig. 10). Some patients who do not have this extra channel rely on calling out loud for their carer when there is a problem. For example, Jill reported: "I remember once when I was having problems I did feel I was sort of passing out… I could feel myself going and I called out to my mum… And she heard me, so she came up…" This communication channel could potentially be provided formally as part of the HHT.

One interaction issue is potential ambiguity on whether the nurse or the technician should be contacted for a particular alarm or problem. When the machine has broken down, the technician should be contacted, and when there is a problem with the patient, e.g. with their fistula, the nurse should be contacted. For some problems, e.g. related to the lining of the circuit or the handling of the machine, it can be tricky for the patient to know who to contact. The HHT design can help with this; e.g., on M2 a flashing spanner (or wrench) indicates a technical problem and a flashing hand indicates a handling problem.

4.2.3. Key flow properties: decision hubs

The third view of the Information Flow Model focuses on key properties of information flow, such as decision hubs.

Table 5
Description of communication processes during the Dialysis activity and the main channels used.

Process	Summary
1. Between Patient and Carer	Communication between the patient and carer may happen while the carer is preparing the patient for treatment, when there are alarms from the machine, or when the patient is suffering from symptoms during dialysis. Communication happens face-to-face (multimodal), or verbally if the carer is in another room
2. Between Patient and Helper	Communication between the patient and helper may happen when there are alarms from the machine, or when the patient is suffering from symptoms during dialysis
3. From Nephrologist to Patient/Carer	Communication between the nephrologist and the patient/carer that is specific to the Dialysis activity happens indirectly, via the dialysis prescription set by the nephrologist. The patient/carer programs the dialysis session with parameters based on the prescription
4. Between Patient/Carer/Helper and Home Nurse	Communication between the patient/carer/helper and home nurse, when there is a patient-related or machine-handling related problem during the Dialysis activity, happens by telephone, or face-to-face (multimodal) when the nurse is visiting the patient
5. Between Patient/Carer/Helper and Technician	Communication between the patient/carer/helper and the technician, when there is a machine-related technical problem during the Dialysis activity, happens by telephone. The technician will typically ask the patient for the alarm/error code displayed on the machine's screen, and then may look up the error code in a manual. The technician also asks the patient some basic questions and tries to visualize what the patient is doing, and then advises the patient on what to do
6. Between Patient/Carer/Helper and Technology System	Communication from the patient/carer/helper to the TS happens via controls on the machine's interface, when e.g. the patient enters the parameters for a dialysis session on the touchscreen. Communication from the TS to the patient/carer/helper happens via the display on the machine's interface, and through auditory alarms and cues
7. Between Patient and Self	Home hemodialysis patients are typically very sensitive to their physiological state and symptoms, and they react accordingly during dialysis. E.g. one patient reported being "very in tune with his body", so he can feel it when a hypotensive episode is about to come, and he takes measures for dealing with it. A patient also has to feel for the correct location and angle when inserting a needle into their fistula, based on the sensations of pain or resistance that they feel

Information decision hubs are points where different information channels meet and different information sources are processed together. For example, a patient or carer acts as an information decision hub in the Dialysis activity when they decide on the treatment parameters for a particular dialysis session by considering information from several channels: the nephrologist's prescription and how the patient currently feels in terms of their wellness. Godbold [14] portrays the renal patient as "a potential information locus: potentially able to confirm information such as medical measurements, make measurements themselves, generate information related to their own sensations, and summarize information about the trajectory of their illness." A carer may also act as a decision hub when routinely checking on the patient or when attending to a problem with the patient: they combine information about the patient's physiological state from artefacts such as a blood pressure monitor with information from other channels, e.g. verbally expressed by the patient, or visually perceived by the carer. One issue related to this is that it can be tricky for the carer to ascertain the current state of the patient, e.g. if the patient is sleeping during dialysis. The technology could help by providing another channel for the carer to get information on the patient's vital signs, e.g. by automatically measuring the patient's blood pressure during dialysis and displaying it on the interface. More generally: in design it is important to review where decisions are made, what information informs those decisions, and how to make that information readily available.

In summary, this model represents how information flows during the Dialysis activity. The analysis demonstrates how cognition is distributed in the home hemodialysis setting in terms of information flows among agents (people and technology), and how a DCog approach can help to identify related interaction strategies/issues. For example, it highlighted the safety–critical importance of the communication channel between the patient and a carer. The next section looks at the social structures involved in the Dialysis activity.

4.3. Social structures

The Social Structures Model of DiCoT [11,38] examines how cognition is socially distributed, through shared goal structures that support robustness and sharing of work, and the development and retention of knowledge within the system. In this study, analyzing how goals are shared among people during the Dialysis activity, and how patients learn to interact with HHT, helped to understand the social context of interactions and to identify related interaction strategies and issues. Shared goals are maintained through communication, so this model approximately overlays the information flow model (though focusing on human agents rather than the TS).

Hutchins [18] describes how a hierarchical structure can map to a goal structure, such that areas of assigned responsibility overlap between superordinate and subordinate to ensure that sub-goals of the overall goal are satisfied. This organizational structure influences the way in which work and responsibility is shared and creates robustness in the system. Fig. 11 shows how goals are shared among actors of the Home Hemodialysis System, during the Dialysis activity. As in Fig. 9, the dotted box serves to show the patient, carer and helper as one unit, and the nephrologist is shown

Fig. 10. Alex's intercom control.

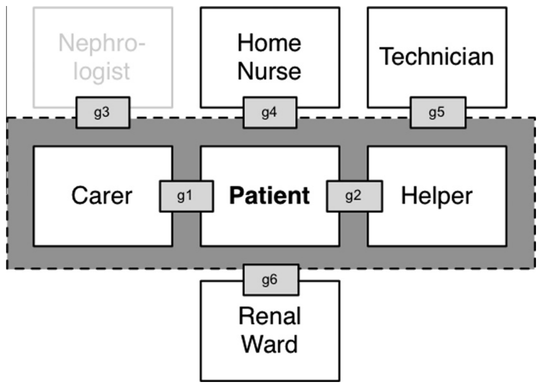


Fig. 11. Shared goal structure for the Dialysis activity.

in a lighter shade. Table 6 describes the shared goals g1 to g6. Because the focus of the study was on home care, the patient is at the centre of this goal structure.

One of the main strategies related to shared goals that was identified is how, if dialyzing alone, some patients take measures so that they can get help from other people if required. For example, they give their neighbor (an informal helper) a spare key to their house, and make sure their phone is next to them during dialysis so that they can call their neighbor. Alternatively, one participant (Bea) makes sure she can easily throw the house key to her neighbor through the window if required, as shown in Fig. 12. This highlights an opportunity for technology to help, e.g. by providing support structures through remote monitoring.

In some situations, e.g. when the patient is passing out, a helper, may need to intervene and suspend fluid removal on the machine and dispense saline to the patient. The design of the machine's interface can help an untrained helper to perform these steps; for example, on M5, pressing a red cross on the display both suspends fluid removal and dispenses a bolus of fluid to the patient. In contrast, on M1, separate actions are required to suspend fluid removal and dispense fluid to the patient; this can make it trickier for a helper to intervene. This highlights the importance of designing HHT such that people with no training can start emergency procedures.

Table 6
Description of goals shared among people in the Dialysis activity.

Goal	Summary
g1. Between Patient and Carer (if applicable)	Shared goals can range from fully preparing the patient and the machine for dialysis to only helping the patient with certain parts of the treatment
g2. Between Patient and Helper (if applicable)	g2 refers to goals shared with a helper, e.g. disinfecting the machine, handing out items, or providing assistance in an emergency
g3. Between Patient/Carer and Nephrologist	g3 includes the dialysis prescription that the nephrologist sets for the patient, and the following of this prescription by the patient when programming a dialysis session
g4. Between Patient/Carer/ Helper and Home Nurse	g4 includes solving patient-related or machine-related handling problems during a dialysis session, and advising the patient on what parameters to use when programming the treatment
g5. Between Patient/Carer/ Helper and Technician	g5 is concerned with troubleshooting a problem during a dialysis session
g6. Between Patient/Carer/ Helper and Renal Ward	g6 involves dealing with any problem that arises during dialysis when the home dialysis unit is closed and the home nurse cannot be reached

4.4. Physical layouts

The Physical Layout Model of DiCoT [11] represents how the physical environment aids actors in their work by examining the physical layout and the arrangement of equipment, and through principles concerning space and cognition, physical naturalness, situation awareness and horizon of observation. In this study, analyzing the physical layout helped to understand the physical context in which patients interact with HHT and to identify related strategies and issues.

4.4.1. Physical layout in the dialysis activity

From a DCog perspective, the physical layout affects communication among actors and access to artefacts. Of the 19 participants in this research, 9 dialyze in a special purpose room, 7 in their bedroom, 1 on her verandah, 1 in his living room, and 1 in her husband's home office. The dialysis site is determined mostly by the availability of a suitable room in the house, existing plumbing arrangements, and the patient's preference. Almost all patients keep all equipment and some supplies in the room where they dialyze, to have everything in one place and facilitate access, but also to protect the aesthetics of the broader HS; in a sense, all the 'clinicalisation' has been done to the room where dialysis is done, so that the rest of the home is spared. Fig. 13 shows an example of a layout in a special purpose room. From left to right, it shows the machine, the weighing scale (circled), the chair on which Alex dialyses, and his dialysis chart (circled). Around the room are different dialysis supplies.

Some strategies are shaped by the location of the dialysis room with respect to the rest of the home. Some carers who do not have a special communication channel to their patient, as discussed earlier, come to the same floor as the dialysis room or to a room nearby at the stage in the treatment when the patient is most likely to feel unwell, so they can be within verbal communication reach of the patient (addressing g2, Table 6). As discussed earlier, HHT could provide a communication channel between the patient and the carer to give the carer more freedom, reducing the need to rely on physical co-location to manage information flow.

As noted above, most patients and their families see the machine as an intrusion into the HS. Many of them cope with this by having a secluded, special purpose 'hospital room' for dialysis, which they avoid going into when they are not dialyzing. Some patients attempt to conceal the machine, e.g. Eva keeps her machine in a closet in her bedroom, as shown in Fig. 14. For

Fig. 12. Bea keeps her house key on the window sill.

Fig. 13. The layout in Alex's dialysis room.

patients who have no choice but to dialyze in their bedroom, this creates a conflict with expectations of the bedroom as part of the broader HS. This stresses the need to design HHT such that it fits with the aesthetics and activities of the HS.

While this principle looked at the physical layout in terms of the location of the dialysis site with respect to the broader HS, the next principle focuses on the arrangement of equipment in the dialysis site.

4.4.2. Arrangement of equipment in the dialysis activity

From a DCog perspective, the arrangement of equipment affects access to information, and hence the possibilities for computation. The arrangement of equipment in the dialysis site influences access to the main artefacts used by the patient during the Dialysis activity, which are: components of the TS, mainly the dialysis machine; dialysis supplies; medical supplies; equipment (e.g. weighing machine); information artefacts (e.g. dialysis chart); communication tools (e.g. telephone); medications; and entertainment (e.g. TV). Most participants keep information artefacts, such as lists of emergency telephone numbers, manuals, and instructions, close by, e.g. on a notice board in the room or framed on the machine itself for ease of access. Fig. 15 shows how Fiona framed the list of emergency telephone contacts on her machine.

Fig. 14. Eva's machine kept in a closet in her bedroom.

One issue is how the limitations of the physical environment at home, as compared to the dialysis unit, can create new extraordinary situations for patients. E.g. both Adam and Cindy (Eric's wife) reported the acid line getting dislodged from the tank by the arterial line, because the latter was taut, and there was a tangle of lines. They struggled to solve the machine's alarm, as they had not been in that situation before and the physical appearance of the lines did not make the problem (or its solution) immediately apparent. Fig. 16 shows an example of the arterial line (red with blood) crossing the acid line (transparent, with a white cap) in Adam's arrangement of equipment. One implication of this is that patients should be alerted during training of problems that can arise in the home environment due to kinking and crossing of lines, so they are better prepared to avoid, recognize and deal with them.

4.4.3. Space and cognition in the dialysis activity

Hollan et al. [17] discusses the role of space in supporting cognition, by supporting choice, problem-solving and planning. One example of the use of space is the use of baskets by Jill (Fig. 4) to organize supplies (and quickly detect when supplies are getting low). Another is a strategy that Adam reported. Adam lays out everything on a table before starting to help ensure that he uses the anticoagulant (step 10 of Fig. 8): there should be nothing left on the table if he has done all the steps (Fig. 17). One issue identified is that the broader HS can interfere with such a strategy. Once, some random objects on the table occluded the anticoagulant, preventing Adam from seeing it, and he forgot to take it. This example illustrates the need to design for patient safety in the context of the broader home environment.

While this principle focused on physical representations that are implicit, the next principle, of physical naturalness, focuses on more explicit physical representations.

4.4.4. Physical naturalness in the dialysis activity

Norman [30] argues that cognition is aided when the form of a representation matches the properties of what it represents, as the mental transformations required to make use of the representation

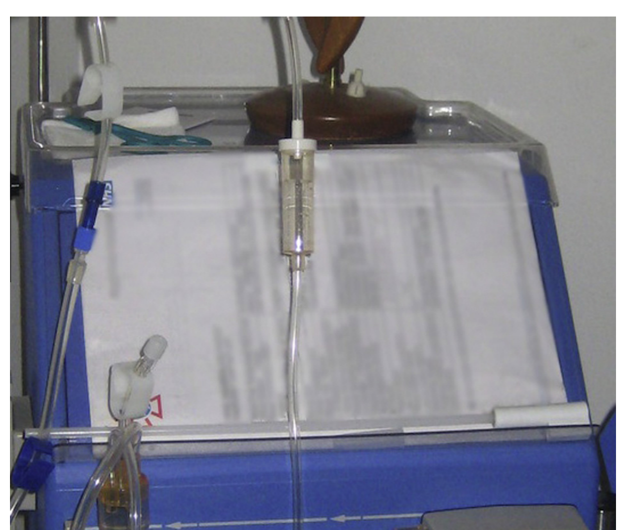


Fig. 15. An emergency contact list framed on Fiona's machine.

are reduced. One issue reported by Jill, who uses M2, is that the caps on the dialyzer for M2 used to be completely blue and red to help distinguish between the arterial and venous ends, but now only very small parts of the caps are colored, making it harder to distinguish between the two lines (particularly important for step 17, Fig. 8). The importance of having clear color-coding for the different ends of the dialysis circuit is stressed in Allcock et al. [1], in which the authors report on a fatal incident that occurred because a patient wrongly connected the ends of the circuit.

The next principle focuses on physical elements that help a patient maintain situation awareness during dialysis.

4.4.5. Situation awareness and horizon of observation in the dialysis activity

Norman [30] notes that, in shared tasks, people need to be kept informed of what is going on, what has happened and what is planned: i.e., to maintain situation awareness. Hutchins [18] notes that situation awareness is influenced by a person's horizon of observation, which is what they can see or hear based on their physical location. Participants were found to rely on visual and auditory elements of the physical environment that are in their horizon of observation, to help them perform certain steps or deal with some situations; for example, people used external information sources to alert them to when to prepare for disconnection (step 19, Fig. 8), and to monitor their blood pressure (step 13, Fig. 8). A less frequently reported example of a physical element is the visibility of the blood's color. Once, the unusual blackish color of the blood indicated to Gina that something was wrong, and she found out later that the anticoagulant that she had used was from a defective batch. This suggests that, though it might be nicer for the patient to not see their blood during treatment, e.g. by having opaque lines, the visibility of the blood can alert the patient to certain problems, and should be retained in the design of HHT.

This model provided an understanding of the physical context in which patients interact with HHT. The analysis demonstrates how cognition is distributed physically in the Dialysis activity, and how a DCog approach can help to identify related strategies and issues. Cognition can also be distributed through artefacts, and this is the focus of the next (and final) model.

4.5. Artefacts

The Artefact Model of DiCoT [11] highlights how the detailed design, structure and use of artefacts aid actors in their work, through principles such as coordination of resources, representation-goal parity, and mediating artefacts. In this study, analyzing how the design and use of HHT and other artefacts support the work of patients helps to identify their interaction strategies and issues.

4.5.1. Coordination of resources in the dialysis activity

Wright et al. [40] present a Resources Model, in which resources are described as abstract information structures that can be internally and externally coordinated to aid action and cognition. Coordination of resources implies, for example, coordinating the plan with the current system state to determine the next goal to be achieved. There are two main aspects to the coordination of resources during the Dialysis activity: the coordination done by the machine, e.g. when it ensures that the patient achieves the correct goal at a particular step; and the coordination done by the patient, e.g. for tasks in the treatment plan that are outside the machine's control. M1 and M5 walk the patient through the procedures for many tasks, helping them learn to perform even some technical operations: for example, changing the filter at the back of the machine. All patients valued the fact that their machine alerts them if they have done something wrong or they forgot to do something, and that it will not go any further until the problem is corrected. For example, Eric's wife feels very confident using the machine because there are a lot of safety features built-in: "if you don't do everything in the set order, the machine will tell you. It is fool-proof and you virtually can't make a mistake with it."

In some situations, the machine does not help with resource coordination, and patients have to coordinate resources themselves. This can be during alarm troubleshooting, which involves the patient internally coordinating resources that represent the state of the system and resources that represent the goal that will fix the problem, or when having to remember to do a step that the machine does not control, which involves the patient internally coordinating a plan resource with state and goal resources. When patients have to coordinate resources themselves, there is a risk of them forgetting to do a particular step or not knowing that a particular step has to be done. According to Terry, a renal technician, most of the calls the technicians get are due to simple handling problems, e.g. when a patient left a clamp on or did not connect something properly (steps 5, 9, 17, 19, Fig. 8). In these cases, the machine points out that something is wrong and that it cannot proceed with the treatment, but it does not identify the problem or the solution. The onus is then on the patient to examine the dialysis setup (the current system state) to deduce what the solution (the goal) is. HHT should ideally coordinate resources in such situations, and for example suggest possible causes of the problem along with solutions, as is the case with M5.

4.5.2. Representation-goal parity in the dialysis activity

Hutchins [18] discusses representation-goal parity as a way in which an external artefact aids cognition by providing an explicit representation of the relationship between the current state and a goal state. The closer the representation is to the cognitive need or goal of the user, the more powerful that representation will be. One common issue is that, in some cases, even though the machine coordinates resources and attempts to tell the patient what the problem is, the machine's message is not always understandable by the patient or does not adequately guide the patient on the course of action. In other words, the interface provides poor representation-goal parity. For example, Adam struggled with a particular alarm he had never encountered before. After spending some time analyzing the setup of the machine, he realized that the bicarbonate probe had got dislodged from the canister. Though the solution was simple, that is just putting the probe back into the canister, the message that the machine displayed for fixing the problem was not comprehensible. Wherever possible, the interface of HHT should provide meaningful messages to the patient that clearly indicate the problem and possible solutions.

The resources that need to be coordinated, especially plan and goal resources, can be represented through other artefacts. The next section focuses on such mediating artefacts.

4.5.3. Mediating artefacts in the dialysis activity

Hutchins [18] discusses the role of mediating artefacts in supporting communication and coordination. Furniss and Blandford [11] describe them as including any artefacts that are brought into coordination in the completion of a task. Patients use a number of mediating artefacts in the Dialysis activity. The main ones are their dialysis chart, their prescription, manuals/booklets with default instructions on procedures, and other artefacts such as emergency contact lists and speed-dial telephone numbers.

Some patients create and use mediating artefacts that represent plan and goal resources. As an example of a user-created artefact, to allow his mother, Heidi, to turn on the machine and start the disinfection process (step 2, Fig. 8) for Bob's machine, Carl (their

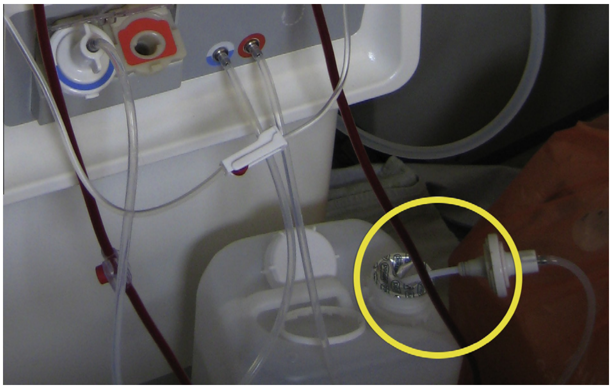


Fig. 16. Crossing of arterial and acid lines.

son) put a set of stickers on the machine's touchscreen. These stickers, red dots, shown in Fig. 18, indicate to Heidi which buttons she needs to press. The disinfection takes about 50 min, and by getting Heidi to start it while he is driving to his parents' place, Carl saves considerable time. This strategy illustrates an externalization of a plan and again highlights how people who are untrained on using the machine may interact with it. To better fit in the context of use, HHT should be designed such that lay people can easily interact with it in case of emergency, as discussed before, but also for initialization tasks such as the disinfection.

Some patients also adapt existing artefacts based on their experiences, so that these are more effective or better suit their needs or preferences. As an example of augmenting a default artefact, several patients add notes to the instruction booklets they received from the hospital, based on their experiences. Fig. 19 shows some notes that Jim added to the default instructions for dealing with hypotension. These notes describe how step 3 in this troubleshooting procedure is achieved with the specific machine that he uses: "by pressing red +" (on right edge). This highlights the importance of such artefacts being of a form such that patients can tailor them to their own situation or augment them to improve their usefulness.

This model focused on artefacts used by patients in the Dialysis activity. The analysis demonstrates how cognition is distributed through artefacts in the Dialysis activity, and shows how a DCog approach can help to identify related strategies and issues. For example, it highlighted the need for representations provided by the interface of HHT to be meaningful to patients.

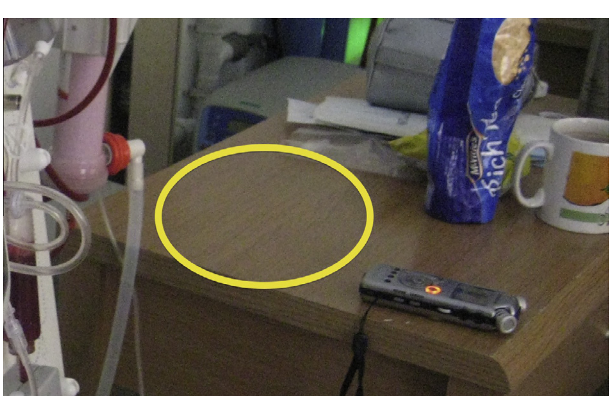


Fig. 17. Table area used by Adam to lay out dialysis items to remember to use them.

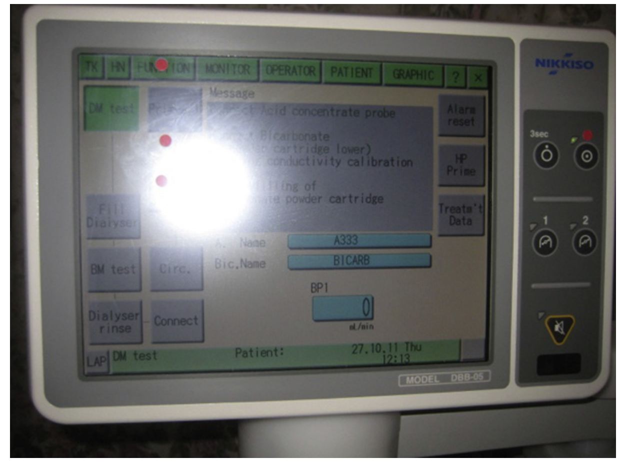


Fig. 18. Four red stickers placed by Carl to guide Heidi to turn on the machine and start the disinfection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

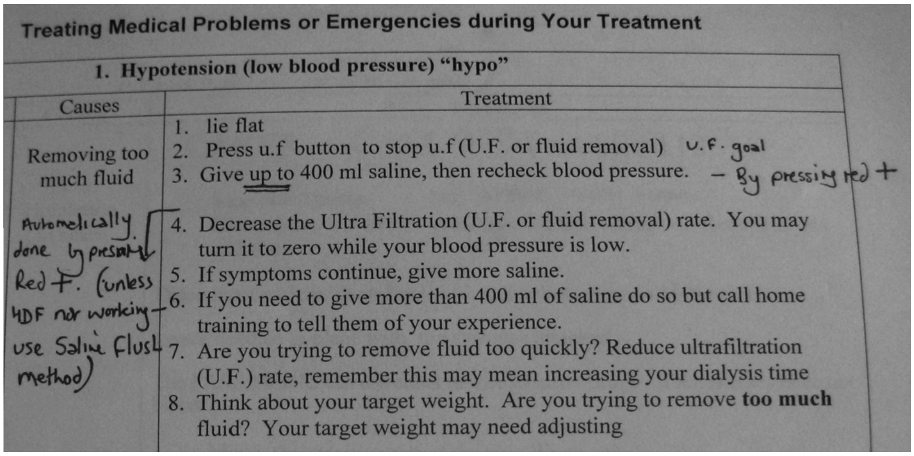
5. Discussion

In this section, the utility of DCog for studying interactions with a HMD in a safety–critical setting such as home hemodialysis is discussed. Due to the lack of studies focusing on understanding interactions with HMDs, there is no literature that allows for comparing and contrasting the DCog approach with other approaches such as Activity Theory [19]. Hence, this section discusses the utility of DCog based on the experience of applying it in this study and of conducting a complementary thematic analysis (based on emergent themes), and on a reflection on the characteristics of the home hemodialysis setting and how a DCog approach addresses these characteristics.

5.1. A distributed cognitive system

This study highlights the properties of home hemodialysis as a distributed cognitive system, in which processes are distributed through people, the physical environment and artefacts. An earlier paper [35] also shows how processes are distributed through time. The information flow analysis summarized the different agents, both human and machine, that help the system achieve its overall goal of providing renal replacement therapy to a patient. The social structures analysis highlighted how processes are distributed among the patient, the carer/helper, the nephrologist, the home nurse, and the technician. The physical layouts analysis highlighted how the physical environment and space is used by patients to support their activity. The artefacts analysis highlighted the importance of different artefacts that patients use to support their activity, and also showed how processes are distributed between the patient and the machine. DCog provided a structure that was absent from the complementary thematic analysis [36].

As described in the 'method' section, both observations and interviews were designed to gather data pertinent to a DCog analysis, with some additional questions relating to safety and user experience. Both data gathering and analysis were based on the DiCoT methodology. The complementary thematic analysis, which was conducted independently and worked with only the interview data, identified and developed emergent themes of learnability, usability and safety. The DCog analysis reported here is theoretically grounded whereas the thematic analysis was data-driven. Inevitably (since both were working from the same data) some of the same issues emerged in both analyses. For example, the issue of making it easy to distinguish the connector ends for correct



Treating Medical Problems or Emergencies during Your Treatment

1. Hypotension (low blood pressure) "hypo"

Causes	Treatment
Removing too much fluid Automatically done by pressing Red +. (unless HDF not working - use Saline flush method)	1. lie flat 2. Press u.f button to stop u.f (U.F. or fluid removal) U.F. goal 3. Give up to 400 ml saline, then recheck blood pressure. – By pressing red + 4. Decrease the Ultra Filtration (U.F. or fluid removal) rate. You may turn it to zero while your blood pressure is low. 5. If symptoms continue, give more saline. 6. If you need to give more than 400 ml of saline do so but call home training to tell them of your experience. 7. Are you trying to remove fluid too quickly? Reduce ultrafiltration (U.F.) rate, remember this may mean increasing your dialysis time 8. Think about your target weight. Are you trying to remove **too much** fluid? Your target weight may need adjusting

Fig. 19. Notes added by Jim to the default instructions from the hospital.

connection emerged in both. However, there were also issues that emerged in one that were absent from the other; for example, the emotional aspects of learning to dialyse at home (feeling "scared" or "panicking") emerged through the thematic analysis but are not within the scope of DCog. This emerged naturally because it was an aspect of experience that people readily articulated. Conversely, the DCog analysis brought out the influences of communications and social structures more clearly than the thematic analysis. These were not topics that participants found it easy to discuss directly, so the structure provided by DiCoT was a useful analytical tool to draw out tacit understanding of the socio-technical context within which people interacted with HHT. Overall, the DCog analysis delivered a theoretical depth and explanatory power that the thematic analysis did not; conversely, the thematic analysis had a direct connection between the insights and the data that was obscured in the DCog analysis, as data was revisited and restructured repeatedly to develop the models.

5.2. A socio-technical, safety–critical, and complex system

Besides being a distributed cognitive system, home hemodialysis is a *socio-technical*, *safety–critical*, and *complex system*. The DCog approach helps to address each of these different characteristics of the system. Obviously, DCog is a suitable approach for studying a setting that is best described as a *system*, as one of the core tenets of DCog is to take a system as the unit of analysis from the outset. It is suitable for studying a *socio-technical* system, as it explicitly considers the roles of both people and technology in the system; from a DCog perspective, both are seen as agents in the system. It facilitates an analysis of how roles could be distributed among people and between people and technology. Additionally, it is suitable for understanding how safety is achieved or compromised in a *safety–critical* system. Safety has been defined as a property of interconnected components of a system [9], and DCog explicitly looks at how the different components of a system work together in achieving its function. For example, the social structures analysis showed how patient safety in the Dialysis activity depends on other people such as a carer, a helper or a neighbor, who may need to intervene in an emergency. Also, the artefact analysis highlighted how safety is provided by the design of the machine, when it ensures that the patient performs the correct step.

In a *complex* system, people are likely to employ strategies to cope with complexity, and these strategies may involve distributing cognitive processes through different media (other people, physical environment, artefacts, time continuum). One aspect of the complexity of home hemodialysis is that the patient needs to do many different tasks, needs to remember to do them, and needs to remember the procedures for doing them. DCog, when applied through a structured method such as DiCoT, is well suited to help understand how people cope with complexity in such a system; the different principles act as theoretical lenses that help identify strategies in which cognitive processes are distributed. Using a broad set of principles to structure analysis allowed this study to identify a broad range of interaction strategies/issues.

Besides helping to understand how actors cope with complexity within that system, DiCoT also allows the researcher to engage with a complex setting [4]. It may be daunting or practically impossible for a researcher to capture and report all phenomena during data gathering and analysis, especially when video-recording is not possible. DCog acts as a theoretical filter that allows the researcher to practically engage with the setting being studied and construct an understanding of it. Given that, typically, with a theoretical filter, some phenomena are given priority at the expense of others, one may question the suitability of DCog as a filter. In the context of understanding how safety is achieved or compromised in a system, the suitability of DCog comes from the fact that it focuses on understanding the very foundation on which a system is built, by looking at how information representations propagate through the system to achieve its function. Therefore, it appropriately directs the focus of the researcher to phenomena that are essential for the system to work as it does. This is especially useful when the researcher is familiarizing themselves with a domain that is new to them, as was the case in this research.

Moreover, the DCog approach does not preclude other focuses of data gathering and analysis, as illustrated in the complementary thematic analysis [36]. A researcher is free to consider other phenomena of interest in their analysis, depending on their research question and the nature of the setting being investigated – e.g. interviewing can be extended to understand participants' affective issues. It is worth noting that, since Activity Theory explicitly considers the motivations of actors during activity, it may provide better theoretical lenses for uncovering interaction strategies and issues at the individual level; because of its systemic focus, DCog does not provide suitable lenses for understanding such phenomena.

5.3. Insights to inform system design

The DCog analysis provides insights on the basic mechanisms that make the system work, but also on current issues in the system. Both types of insights are valuable in informing design. In this study, the analyses through the different DiCoT models pointed to safety-related interaction design issues and potential design improvements. The following are examples. The information flow analysis highlighted the importance of having a communication channel between the patient and the carer during dialysis, especially when the carer is in another part of the home during dialysis. The social structures analysis showed that the interface of HHT should be designed such that an untrained person can interact with HHT in case of emergency. The physical layout analysis stressed the importance of patients being able to easily distinguish between different connection ends, to reduce the risk of wrong connections. The artefact analysis indicated the need for the device to provide better guidance to patients on the causes and solutions of alarms.

More generally, this study has shown that the design of HHT should be better aligned with the needs of home patients and with likely scenarios of use in the home. The findings also highlight the potential to improve the experience of renal patients by designing HHT such that it helps patients to cope with the physical, social, medical and cognitive complexities of home hemodialysis treatment. Additionally, the findings indicate that the patient experience could be improved by designing home medical devices taking into account the broader context in which patients interact with the devices.

5.4. Variations in technology and practices

The technology and practices involved in home hemodialysis vary over time and across hospitals and countries. Practices evolve over time, e.g. as clinicians learn from experiences of previous patients to improve the experience of future patients. Technology evolves, e.g. as manufacturers improve the design of the technology based on patients' experiences. Technology and practices also vary across hospitals and countries. For example, M3 is portable, unlike the other machines, and works with a disposable cartridge, such that the lining of the circuit is simplified. As an example of a variation in practice: in the case of H1, there is a home nurse who visits the patient on a monthly basis, whereas in the case of H3 no nurse routinely visits the patient at home.

Despite such variations, the system that provides home hemodialysis treatment to the patient fundamentally remains a distributed cognitive system, the *configuration* of which varies with variations in technology and practices. Moreover, other types of supported home therapies are likely to be distributed cognitive systems as well, as illustrated by the study of Obradovich and Woods [32] discussed above. Even a therapy that involves only a patient and a smart medical device is a distributed cognitive system, as processes will be distributed between the patient and the device. This is the basic premise of the Distributed Information Resources Model [40], which provides a way to analyze Distributed Cognition in interactions between an individual and a technology, in terms of resources for action. Therefore, DCog is a useful theoretical framework for understanding interactions with HMDs such as HHT, especially when the research aims to understand how safety is achieved or compromised.

6. Conclusion

In this study on patients' situated interactions with HHT, it was found that cognitive processes are distributed in the home hemodialysis setting through people, the physical environment, artefacts and the time continuum (reported by [35]. By explicitly supporting reasoning about such distribution of cognition, a DCog approach helps to identify patients' strategies and issues, including those with safety implications. The empirical findings show the need to design HHT such that it is better aligned with the needs of home patients and likely scenarios of use at home, and such that it helps patients cope with the complexities of the treatment.

In our work to date, we have developed the DiCoT approach and tested its learnability [4]. We have also applied it to analyse situations with greater variability (control rooms, hospital wards and now home use). In this paper we have drawn out some implications for design. In future work, we aim to test the approach further, in terms of how well it supports prediction (based on possible future designs), and whether and how it can be made usable by and useful to practitioners (see, for example, the account by Spencer [37] on adapting Cognitive Walkthrough for use in practice).

The work reported here has shown that, besides being suitable for understanding interactions in clinical settings, DCog is a useful theoretical framework for understanding safety–critical interactions in the home with a HMD such as HHT.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgments

The authors are grateful to all participants for the time, expertise and experiences they shared with us, and to all hospital staff who facilitated this research. We are also grateful to anonymous reviewers for constructive criticism of an earlier version of this paper. This research is funded by the UK Engineering and Physical Sciences Research Council Grant EP/G059063/1.

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