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Distributed Cognition: Understanding Complex Sociotechnical Informatics

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Abstract. Distributed cognition theory posits that our cognitive tasks are so tightly coupled to the environment that cognition extends into the environment, beyond the skin and the skull. It uses cognitive concepts to describe information processing across external representations, social networks and across different periods of time. Distributed cognition lends itself to exploring how people interact with technology in the workplace, issues to do with communication and coordination, how people's thinking extends into the environment and sociotechnical system architecture and performance more broadly. We provide an overview of early work that established distributed cognition theory, describe more recent work that facilitates its application, and outline how this theory has been used in health informatics. We present two use cases to show how distributed cognition can be used at the formative and summative stages of a project life cycle. In both cases, key determinants that influence performance of the sociotechnical system and/or the technology are identified. We argue that distributed cognition theory can have descriptive, rhetorical, inferential and application power. For evidence-based health informatics it can lead to design changes and hypotheses that can be tested.

Keywords. Distributed cognition, Sociotechnical, Informatics, DiCoT

Learning objectives

After reading this chapter the reader will be able to:

1. Summarise the theory of distributed cognition.
2. List different methods and frameworks that have been developed to facilitate the application of distributed cognition.
3. Give examples of how distributed cognition has been applied in health informatics.
4. Explain how distributed cognition can be used in formative and summative stages of a project life cycle.
5. Explain how distributed cognition can lead to design ideas and testable hypotheses.

1. Introduction of distributed cognition

Distributed cognition [1] is a theory that represents a radical departure from traditional notions of cognition focused on information processing in the brain. Distributed cognition focuses on information processing in sociotechnical systems, which we dub

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sociotechnical informatics. Sociotechnical informatics includes the propagation and transformation of information across natural and engineered computational systems at a sociotechnical level. For distributed cognition, the argument is that individuals form a tightly coupled system with their environment in such a way that they employ and exploit external structures in cognitive tasks, so the task of cognition is actually distributed [2]. For example, ambulance dispatch coordinators have cards (representing incidents) and a tray of slots (each slot representing an ambulance) so they can easily see what ambulances are assigned to what incidents and how many ambulances they have free without relying solely on their internal memory [3]. Furthermore, we can configure sociotechnical systems and design external structures to influence how information is transformed and propagated in teams of individuals. For example, in the London ambulance control room dispatch teams are organised by region so if they have an incident between two regions one team can more easily communicate with the team beside them about resource allocation [3]. Modern healthcare informatics faces increasing challenges in how information processing systems should be designed and organised, especially as systems become more distributed, interconnected and complex. Distributed cognition can help to understand complex sociotechnical informatics.

1.1. Distributed cognition: The basics

Distributed cognition was pioneered by Edwin Hutchins and colleagues in the early nineties. His book, *Cognition in the Wild*, is the seminal text in the area [1]. Distributed cognition distinguishes itself from other approaches by taking the information processing metaphor of the mind and suggesting that this should not be limited to the brain, broadening what can be considered part of the cognitive system [2]. Its unit of analysis is not the individual mind but a complex cognitive system, which is essentially sociotechnical in nature [4]. It is complex because it involves different artefacts and people, over time and physical space; it is cognitive because it is focused on information processing; and it is a system because it involves elements that interact to perform a task or achieve a goal. These defining features resonate well with complex sociotechnical informatics.

One of the earliest and best-known applications of the theory involved considering a cockpit as a complex cognitive system comprising the pilots, instruments, controls and reference materials [5]. Hutchins [5] examined the intricacies of how this system worked as the design of the tools and instruments, the way the pilots sat, and the way they communicated could influence performance. He showed that distributed cognition is not simply about offloading memory into the environment, whereby operators have extra reference material to aid recall, but that their tasks can fundamentally change depending on how cognition is distributed. For example, Hutchins described how *speed bugs* are adjusted on a speed dial to indicate safe parameters for landing speeds depending on an aircraft's weight. These do not act solely as an additional reference point in case the pilot cannot recall the figures that define the parameters for safe landing speeds: they actually provide a spatial range that the speed dial indicator should remain within, which is a very different form of interaction. Hutchins [5] includes these interactions to account for the cockpit system's memory.

Distributed cognition has also been shown in carefully constructed laboratory experiments. For example, Maglio and Kirsh [6] showed that experts sometimes make *epistemic actions* in the environment to simplify a problem space rather than trying to solve the problem in their head before acting. Also, Zhang and Norman [7] showed that participants handle the same problem differently depending on how it is represented; i.e., the physical affordances of items involved in the problem's representation can complicate, simplify or otherwise transform the problem space. In both studies the determinants of performance go beyond the individual mind to include cognitive processing across external artefacts.

Distributed cognition theory proposes that cognition can be distributed in three main ways [2]:

1. Cognitive processes may be distributed across members of a social group.
2. Cognitive processes may involve coordination between internal and external (material or environmental) structures.
3. Processes may be distributed through time in such a way that the products of earlier events can transform the nature of later events.

Essentially this approach highlights how individuals' cognitive processes extend into the environment, and how groups process information using different artefacts and structures across different spaces and over different periods of time.

1.2. Applying distributed cognition theory using DiCoT

Some commentators have criticised distributed cognition for being too unstructured for easy application, i.e. there is no 'off the shelf' methodology [8]. Cognitive ethnography is proposed as the main approach for studying cognition in the wild (e.g. interviews, surveys, observations and video and audio recording) [2]. However, cognitive ethnography is a group of techniques, which lack further structure and analytical support, i.e. there is still a big challenge for researchers to know what to look at, how to look, and how to link theory to data. To fill this gap, different methods have been developed that offer more support and instruction: the Resources Model [9]; Distributed Cognition for Teamwork (DiCoT) [10]; Determining Information flow Breakdown (DIB) [11]; and Event Analysis of Systemic Teamwork (EAST) [12]. The remainder of the chapter focuses on DiCoT, which we propose is the most developed method for understanding the details of situated interactions, rather than more exclusive focus on abstract information flows, networks and the coordination of information resources.

DiCoT [10] draws upon the structure of Contextual Design [13] to provide more analytical support. Distributed cognition's focus "has always been on whole environments: what we really do in them and how we coordinate our activity in them" [2, page 174]. Contextual design also has this focus but is not underpinned by a theoretical perspective. DiCoT extends this approach to use five interdependent models:

- Information flow model – focuses on how information is transformed and propagated in the system, taking tasks, activities and processes into account.
- Artefact model – focuses on how the design of tools, technologies and external representations influence the information processing of the system.
- Social model – focuses on the different roles people play in the system, with their different knowledge, responsibilities, skills and expertise.
- Physical layout model – focuses on how things are arranged in the physical environment and how this impacts the flow of information.
- Evolutionary model – focuses on how cognition is distributed over time, which includes short and medium-term actions to plan and prepare work, and long-term considerations such as how the system has evolved over time.

Each of these models has associated principles extracted from the literature on distributed cognition [10]. Table 1 shows how some of these are applied. These distributed cognition principles have been shown to help analysts gain further insight into complex sociotechnical systems compared to contextual design alone [14]. These principles should not be seen as a comprehensive and prescriptive check list of distributed cognition features, but as a set of sensitizing concepts to enrich what can be seen and described – some are likely to be relevant in a given context and some will not be. This approach has been applied in different contexts by our group and others (e.g. [15, 16]).

DiCoT-CL is an extension of DiCoT, which adds 'concentric layers' to each of the models to encourage the analyst to think about micro, meso and macro layers of distributed cognition [17]. DiCoT-CL has been applied to evaluate the design and use of a blood glucose meter on a ward [17] and to investigate the safety around infusion practices on a ward [18]. In both cases we treat the micro as the layer that is closest to the interactions to do with the device, procedure or technology under study, e.g. by the bedside; the meso is the layer out from this which might include different professionals as a team, e.g. at the scale of the ward; and macro is the layer that might be as broad as the hospital or above, e.g. national guidance. These different layers have been effective in showing that determinants for success and failure in a system might not be proximate to technology use but might be further away in space and time. For example, the configuration of infusion pump alarms in the hospital layer had downstream consequences for staff and patients in the micro layer [18].

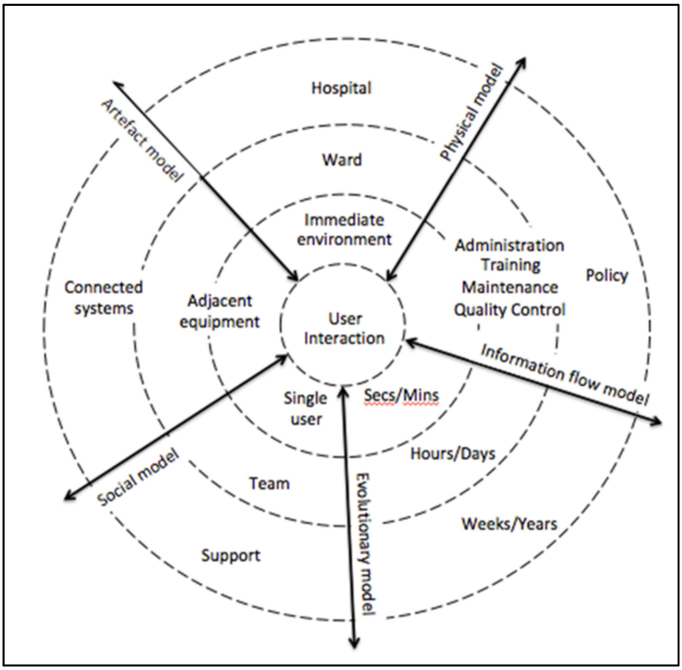

Figure 1. DiCoT-CL framework has three concentric layers of the sociotechnical system, where each layer is divided into five areas that reflect the themes of the different DiCoT models, i.e. information flow, artefact, physical, social and evolutionary models (adapted from [17]). Reproduced with permission.

Halverson [19] makes the point that distributed cognition does not explicitly name its concepts and constructs, which makes it harder to apply. DiCoT and DiCoT-CL advance the field by making explicit the concepts that support reasoning about a system in terms of distributed cognition, which are called 'principles' in DiCoT (e.g. see application of a sample of distributed cognition principles in Table 1). These principles are organised under the five DiCoT models that act as constructs for distributed cognition. DiCoT-CL adds constructs in the different layers of the sociotechnical system, and the proposition is that these layers are part of and nested within another. Naming these principles encourages deeper insight because they refer to more abstract sociotechnical issues, configurations and patterns in the data. The principles go beyond mere description and improve the rhetorical power of distributed cognition because the theory can help frame arguments about what is influencing the performance of the system, e.g. decisions in one layer might have an impact on performance in another layer.

Hollan et al. [2] offer a framework describing how integrated research activities using distributed cognition theory might be carried out. The framework links distributed cognition theory to ethnography, experimentation and testing, work materials, and workplaces. The order of these elements in the framework can be adapted for different studies; for example, observational work to identify key determinants for system performance might be conducted to inform the design of experimentation and testing; or it might be that results of tests or design processes away from the workplace can then be trialled to see how they perform in the messiness of practice.

2. Use of distributed cognition in health informatics

In this section we give a brief overview of how distributed cognition theory has been used in health informatics before presenting two use cases to demonstrate how DiCoT and DiCoT-CL can be used in both formative and summative stages of a project life cycle.

2.1. Overview of how distributed cognition theory has been used in health informatics

The case for distributed cognition's relevance for health informatics has been argued previously [20]. It lends itself well to exploring how people interact with technology in the workplace, issues to do with communication and coordination, how people's thinking extends into the environment and sociotechnical system architecture and performance more broadly. Published studies using distributed cognition in health informatics journals and related areas include:

- Hazlehurst et al. [21], who used distributed cognition to help identify six types of communication exchange that help situation awareness arise from coordinated work and achieve successful performance between surgeons and perfusionists in cardiac surgery. They investigated activities, artefacts, resources, constraints and information flows.
- Cohen et al. [22], who used distributed cognition to analyse morning rounds and handovers in a psychiatric emergency department to explore how error commission, detection and recovery are an integral part of cognitive work. They identified instances of perceived violations and miscommunication.

- Hussain and Weibel [15], who used DiCoT to explore the information flow of infection control information in critical care and consider the design of a novel touch screen and badge reader.
- Sarcevic and Ferraro [23], who examined the efficiency of electronic documentation in a fast-paced medical setting through the lens of distributed cognition, using cognitive ethnography to understand the information flow among team members and how information was shared, stored and documented.

2.2. Two use cases using distributed cognition for health informatics

We present two use cases at different stages of the project life cycle: the first case at the formative stage of the project life cycle where we are still developing an understanding of the key determinants for what, how, when and why patients use patient-held information about their medication (PHIMed); the second is an example of a study at the summative stage of a project life cycle where we evaluate the design and use of infusion devices already in practice.

2.2.1. Use case 1: Patient-held information about their medication (PHIMed)

PHIMed is defined as any patient-held information such that an editable list of current medications can be carried, regardless of whether or not other functionalities are also available; this can include paper and electronic tools [24]. Patients can be concerned about receiving appropriate treatment, especially where information breakdowns might occur in a fragmented healthcare system. For example, general practitioner surgeries, hospitals, and community pharmacies do not routinely share data in the National Health Service, increasing the chance of error. PHIMed helps fill the gaps and prevent errors. A specific example is that as a result of viewing a patient's PHIMed a community pharmacist stopped the patient purchasing an over the counter medication which would have been unsafe for them to use. [25] However, how PHIMed is best used, whether it affects patient outcomes and its key determinants for success are not known.

Distributed cognition was selected as the theory for investigating design and use of PHIMed. Distributed cognition seemed like a good fit since we are interested in the design and use of an artefact (i.e. PHIMed), how this may play a role in supporting cognition and decision making of healthcare professionals and patients, and how the use of PHIMed could have wider effects on the system such as improving resilience to errors and enhancing patient activation.

DiCoT is being used to provide concepts and constructs to inspire thoughts and questions that we might not have asked without the theory. Early on in the study we discussed the application of the theory and used it to brainstorm whether and how concepts and constructs might be applicable (see Table 1 for examples). These early ideas informed data gathering and analysis, but importantly will also be tested by empirical data. In this way DiCoT supported sense making at the very early stages of the project lifecycle, helping us to generate questions and explore potential determinants of success for PHIMed that can then be tested.

Table 1. Examples based on the PHIMed project showing how DiCoT principles can generate thoughts and questions before a project has started. The models show the area of Figure 1 that these principles are related to, however they are interdependent models so in practice there is a lot of overlap between models.

Principle (and associated model)	**Description of principle**	**Application to PHIMed project**
Information hubs (Information flow model)	Information hubs are a central focus where different information channels meet and different information sources are processed together, e.g. where decisions are made on various sources of information.	Patients may consider their general practitioner or healthcare record as a hub. However, others may see their care as fragmented so they are the hub, or they may perceive their PHIMed to act as a hub where there medications are concerned.
Behavioural trigger factors (Information flow model)	In teams it is possible for individuals to operate without an overall plan as each member only needs to know what to do in response to certain localfactors. Individuals may also base their behaviour on their perception of local circumstances. These initiating factors can be dubbed 'trigger factors' because of their property to trigger behaviour.	What was the reason for starting to use PHImed? What triggers someone to show PHIMed to a particular healthcare practitioner or to take it to a particular consultation? What triggers someone to update their PHIMed?
Situation Awareness (Physical layout model)	One of the key things in shared tasks is to keep people informed of what is going on, what has happened and what is planned. This can be influenced by how accessible the work of the team is. For example, in large control rooms the fact that an operator is in one area may lead to the correct inference of what they are doing, as that area pertains to certain activities.	This seems really important because different healthcare practitioners may lack situation awareness and PHIMed can help improve situation awareness in fragmented pockets of care.
Horizon of observation (Physical layout model)	The horizon of observation is what can be seen or heard by a person. This will differ for each person in an environment depending on their physical location, the activities they are close to, what they can see and hear, and the manner in which activities take place. The horizon of observation of a person refers to the scope of information input, whereas situation awareness is about the inferences that are made from this information.	Different healthcare practitioners will have very different horizons of observation, as will the patient and carer. Different technologies and PHIMed may influence the healthcare practitioner's horizon of observation.
Socially distributed properties of cognition (social model)	"The performance of cognitive tasks that exceed individual abilities is always shaped by a social organisation of distributed cognition. Doing without a social organisation of distributed cognition is not an option. The social organisation that is actually used may be appropriate to the task or not. It may produce desirable properties or pathologies. It may be well defined and stable or may change moment by moment; but there will be one wherever cognitive labour is distributed, and whatever one there is will play a role in determining the cognitive properties of the system that performs the task" [1, pp 262].	The cognitive tasks involved in looking after a patient, which could include treating different conditions, appear to be distributed between different specialists and individuals. How are these individuals distributed and coordinated? What impact does this have on patient care and decisions about medication optimisation?

2.2.2. Use case 2: Safety around infusion devices on a haematology ward

This study sought to evaluate safety around infusion devices on a haematology ward [18]. Using DiCoT-CL we explored determinant factors in the safety of infusions on the ward at the micro, meso and macro layers of the sociotechnical system. We present this as an example of how distributed cognition can be used in the late stages of the project lifecycle, post-implementation, to discover interactions that impact the performance of technology in practice. We spent 120 hours on the ward, shadowing and interviewing nurses, and observing infusion preparation and administration on the ward. DiCoT-CL was used for data gathering and evaluation; i.e., we attended to the five models, three different layers and the distributed cognition principles.

Using DiCoT provided leverage to investigate the complex sociotechnical informatics that comprises infusion practice on the ward. We found that infusion safety was influenced by artefacts, social networks, the flow of information, the physical layout of the ward and interactions over time. Issues with design of infusion pump alarms, medication storage, prescription information, and hospital bed management systems were noted. Safety is affected by the co-evolution of structure (e.g. the design of pump alarms), agency and workarounds (e.g. telling some patients how to silence their alarms), and deviations (e.g. patients silencing the wrong alarms) [18].

3. Explanation of success or failure of health information systems

This section describes determinant factors in the success or failure for the above mentioned use cases and how distributed cognition theory has supported the investigation and explanation of such factors.

3.1. Use case 1: Preliminary results in what triggers the use of PHIMed

DiCoT helped us start to think about the sociotechnical system that PHIMed may be embedded within. For example, early empirical feedback suggests that not all patients use PHIMed (i.e. they have different information requirements) but where it is used it can be recognised as an important artefact for supporting information flow around patient care. Before empirical work began we were already thinking about what contextual factors might be a ‘behavioural trigger’ to use of PHIMed (see application of DiCoT principles in Table 1). One conjecture was that patients who do not use PHIMed may perceive their general practitioner and/or medical record as an effective ‘information hub’ for their care (Figure 2.a), and that patients who do use PHIMed experience a more fragmented healthcare service that does not have an effective information hub. In this latter scenario the patient realises that they are the common feature in different consultations and act more like an ‘information hub’ in the absence of an effective hub on the healthcare side (Figure 2.b). Figure 2 shows two contrasting social networks inspired by the social model of DiCoT, which lead to different thoughts about what factors determine when PHIMed might be used and in what circumstances PHIMed might be most useful. These different patterns of distributed cognition are important for reflecting on who to target, when and in what circumstances to improve adoption and use in a future PHIMed intervention. We are continuing to test these and other conjectures in focus groups and interviews with healthcare professionals, patients and carers.

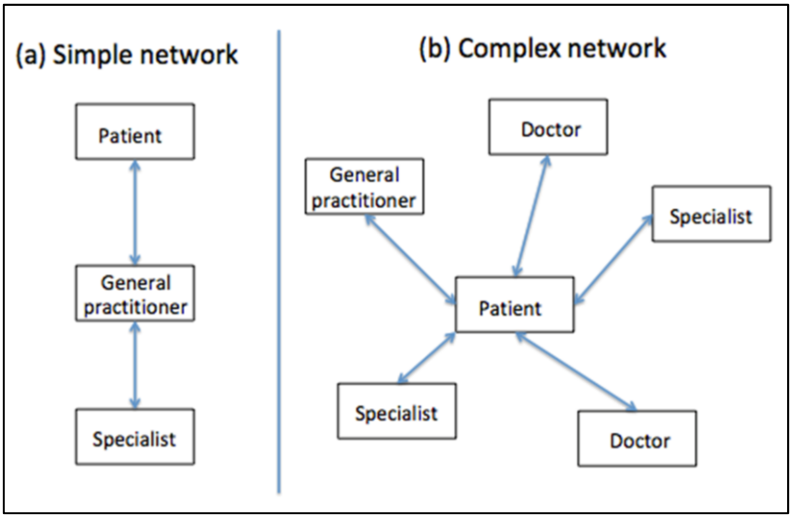

Figure 2. (a) An example of a simple social network where the general practitioner is seen as the central hub for patient information with only one other specialist; (b) An example of a complex social network where the patient is the central hub within fragmented healthcare services involving various doctors in secondary care and other specialists.

3.2. Use case 2: A problem between alarm design and barrier nursing

One of the most striking findings for safety around infusion devices on the haematology ward was a tension between the design of the infusion pump alarms and the procedures for barrier nursing [18]. The infusion pumps were designed to alarm ten minutes before the infusion was due to complete (a 'pre-alarm'). This was standard across the hospital and was intended to alert nurses so they could prepare for when it finished, e.g. prepare the next infusion. However, the haematology ward used many infusions and every patient needed barrier nursing to prevent spread of infection, requiring nurses to wash their hands and put on gloves, gown and mask before entering the patient's room. Reaching the pump to silence the alarm was therefore costly in terms of time. Once the nurse had silenced the pre-alarm they could not wait in the patient's room for ten minutes so they would go out and try to do something else before being called back for the actual alarm on completion of the infusion.

The physical layout of the ward also meant that it was difficult to hear pumps alarming from the corridor, partly because there was an ante-room between the main corridor and each patient's room. So, nurses were effectively relying on the pump alerting the patient, the patient pressing the call bell, and the nurse reacting to the call bell. Some patients expressed frustration at this process. One patient did not want to disturb the nurses, knowing how busy they are, so she sat next to the pre-alarm beeping for ten minutes before calling the nurse to attend to the pump.

A downstream consequence of the frustrations for staff and patients caused by the pre-alarm was that nurses would sometimes break with protocol and coach patients on how to silence the alarms. However, this would depend on the nurse and patient, e.g. patients who were not deemed competent would be discouraged from interacting with their infusion pump even if they tried to do it themselves. It was suggested by one member of staff that patients may have inadvertently silenced a low power warning thinking it was a pre-alarm, leading to the infusion pump stopping.

DiCoT-CL helped to describe the artefact, physical layout and social interactions that were contributing to this issue. There were also factors at play in different layers of the sociotechnical system. The main issues were being experienced at the micro and meso layer on the ward. Nurses complained that it was the way the pumps were designed, and there was nothing that could be done about it at the macro layer. However, further investigation revealed that this was a design configuration issue that could be adjusted by the hospital, at a different place in the macro layer. The analysis showed misunderstandings about the determinant factors contributing to this issue, which had different downstream consequences for staff and patients. Haematology services have now moved to a different hospital, but it seemed clear, through application of distributed cognition theory, that the configuration of the pre-alarms and barrier nursing was not working for staff and nurses. However, the pumps could have been reconfigured and tested using staff and patient satisfaction scores; efficiencies could have also been gained in the reduction of alarms. Again, distributed cognition can lead to testable hypotheses.

4. Discussion

Distributed cognition theory is relevant for the understanding of complex sociotechnical informatics. Cognitive concepts can be applied to sociotechnical systems to elucidate how information flows across artefacts, social networks, over different physical configurations and different spans of time. The theory had been around since the nineties, but more detailed support to facilitate its application has only been developed more recently. Many applications of distributed cognition theory provide description and explanation of how information flows in a sociotechnical system. However, it also lends itself to considering determinant factors for the success and failure of technology, and how the technology might fit (or not) in context. This can lead to design ideas and hypotheses that can be tested. For example, the use cases presented here show how distributed cognition can inform the design of PHIMed and in what circumstances patients might be most receptive to it; and how distributed cognition can be used to evaluate systems that have been already been deployed.

Like all theories, distributed cognition has strengths and weaknesses. Distributed cognition encourages a level of description about a system or process that lends itself to developing design ideas, but it may not readily emphasise the role of individuals or emotions as it focuses on systems and more observable functional issues [19]. This potential limitation is partially dependent on how rigidly one applies the theory. For example, more inductive ethnographic techniques can include interesting phenomena that might not readily fit the theory. Similarly, DiCoT can be applied in more or less rigid ways. Those unfamiliar with DiCoT may like to treat its models and principles as a check list, but we recommend its use in a semi-structured way to enrich what can be seen in context but not be too limited by the theory. Even with semi-structured use, DiCoT adds structure that draws attention to certain features and away from others, which should be reflected on by those who use it. Halverson [19] says that it is not clear whether success from the theory is from the theory itself or its commitment to ethnographically collected data. However, at least in the PHIMed example above we have seen that distributed cognition concepts and constructs can inspire thoughts and questions before empirical work has begun (Table 1), which suggest value lies in the theory itself. Since the theory is more accessible through the articulation of its concepts and constructs, and the need for such theories in health informatics and other domains is rising due to growing complexity of joint social and technical systems, distributed cognition is ready and relevant for grappling with twenty first century issues.

Following Halverson's [19] four categories for assessing the utility of theory: we believe distributed cognition provides *descriptive power* (e.g. DiCoT helped describe and make sense of activities through distributed cognition concepts and principles); *rhetorical power* (e.g. in terms of argumentation DiCoT-CL helped frame and articulate how macro level decisions were having negative downstream impact on the haematology ward); *inferential power* (e.g. we infer that patients who are most likely to use PHIMed would be those who experience complex and fragmented healthcare services); and *application power* (e.g. targeting PHIMed interventions towards patients with complex and fragmented care could have a higher likelihood of impact and changing the configuration of the pre-alarm on the haematology ward could have a positive impact on staff and patients, both of which could be tested).

Teaching questions for reflection

1. What tools and artefacts related to health informatics exemplify how an individual's cognition extends into the environment?
2. What complex sociotechnical systems can you describe that have important aspects of health informatics within them?
3. How would a research project evaluating electronic health records look different when planned from a traditional individualistic perspective versus a distributed cognition perspective?
4. What are the strengths and weaknesses of distributed cognition theory?

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