Applying Distributed Cognition Theory to Agile Requirements Engineering

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Abstract. [Context & Motivation] Agile Requirements Engineering (ARE) is a collaborative, team-based process based on frequent elicitation, elaboration, estimation and prioritization of the user requirements, typically represented as user stories. While it is claimed that this Agile approach and the associated RE activities are effective, there is sparse empirical evidence and limited theoretical foundation to explain this efficacy. **[Question/problem]** We aim to understand and explain aspects of the ARE process by focusing on a cognitive perspective. We appropriate ideas and techniques from Distributed Cognition (DC) theory to analyze the cognitive roles of people, artefacts and the physical work environment in a successful collaborative ARE activity, namely requirement prioritization. **[Principal idea/results]** This paper presents a field study of two early requirements related meetings in an Agile product development project. Observation data, field notes and transcripts were collected and qualitatively analyzed. We have used DiCoT, a framework for systematically applying DC as a methodological contribution, to analyze the ARE process and explain its efficacy from a cognitive perspective. The analysis identified three main areas of cognitive effort in the ARE process as well as the significant information flows and artefacts. Analysis of these have identified that the use of *physical* user story cards, specific facilitator skills, and development of shared understanding of the user stories, were all key to the effectiveness of the ARE activity observed. **[Contribution]** The deeper understanding of cognition involved in ARE provides an empirically evidenced explanation, based on DC theory, of why this way of collaboratively prioritizing requirements was effective. Our result provides a basis for designing other ARE activities.

Keywords: Distributed Cognition · Agile · Requirements prioritization

1 Introduction

The development of a shared understanding of user requirements between the client and development groups is fundamental to the design and development of software that satisfies the stakeholders' needs. In Agile Requirements Engineering (ARE) the effort

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to collaboratively understand user requirements, generally represented as user stories, occurs frequently, in every sprint. Each sprint, the focus is given to identifying and deepening understanding of user stories that are high value and prioritizing them for development in the next sprint [1]. Regular ARE activities include team meetings for requirements prioritizing, elaboration, estimation and planning. The emphasis in Agile RE is on regular face-to-face communication and collaboration among the client stakeholders and development team to develop and deepen this shared understanding of the requirements [2]. While it is claimed that the Agile approach is effective in supporting the achievement of these RE goals, there is little detailed empirical evidence and limited theoretical foundations for these claims. This paper proposes viewing ARE as a collaborative distributed cognitive process and appropriates a multidisciplinary framework, Distributed Cognition theory (DC), as a theoretical foundation for understanding and explaining the efficacy of ARE activities. Viewing ARE as a collaborative cognitive (information processing) process is a natural perspective, given the emphasis on communication (information flows and processing), and the fundamental cognitive goals of shared user requirements understanding. DC is a good fit to describe and understand this since it provides a theoretical foundation for how work is done in complex, collaborative team-based activities such as ARE, where the cognitive activities are socially distributed and interactions with work objects and the work environment are important [3]. A DC analysis of such work can have the applied aim of explaining and understanding the efficacy and shortcomings of current workspaces, work practices and technologies used, as in our case.

Although RE is recognized as a complex socio-technical set of activities involving people, tools and artefacts, very few studies have attempted to understand the nature of RE activities through the lens of DC theories. The applications of DC have been demonstrated in areas such as creative requirements engineering [4], semi-structured creative processes in group work [5], knowledge management in requirements engineering [6], distributed requirements engineering [7], Model-Driven requirements [8], and open source software requirements [9, 10]. Although not focused solely on RE, Sharp and Robinson [11–13] used the DC framework to analyze the collaborative work in the XP team development process in order to highlight the potential problem areas in the activity. Outside RE the DC approach has been used to analyze the computer-supported co-operative work (CSCW) for discovering the effectiveness of collaborative technologies [14, 15], community of practice [16], effective design of teamwork systems [3, 17] and in the field of HCI to analyze the development of interactive systems [18, 19].

The existing literature justifies the use of the DC framework and its theoretical underpinning for understanding collaborative RE practices. Our study differs from existing DC literature by applying the DC analysis to the ARE context, applying it to a shorter time frame (specific time-boxed meetings), and how the achievement of the specific cognitive goals of the observed ARE activity are supported through distributed information processing as cognition. It can be expected that this detailed DC analysis explains the efficacy of some characteristics of the process involving interactions between people, the room layout and artefacts, and may also suggest some possible process improvements.

In our field study, a specific ARE activity, early requirements prioritization (RP), is chosen as the focus of our DC analysis, but the principles and research approach

could be applied to any collaborative aspect of ARE, which is the aim of our future research. Early RP meetings were selected as an example of applying DC theory to ARE because, RP is iterative, frequent and central to the agile way of working. Agile RP is collaborative and, particularly in the early requirements phase, it can be complex and challenging cognitively. The RP process in practice can vary widely, with context-dependent adoption of many processes and techniques [20]. The cognitive complexity of Agile RP can be inferred from the plethora of RP processes and techniques described in the literature [21, 22].

In summary, this paper reports on an in-depth field study of an aspect of the collaborative Agile RE process taking a cognitive perspective. It is based on observational field work of two early-phase RP meetings in preparation for the first development sprint. The transcribed audio, video and field notes collected in the meetings are analyzed to understand the strengths and weaknesses of the observed RE activity from a distributed cognition perspective. Based on DC theory we identify the significant interactions between people, the physical work environment and work-related artefacts, viewed as a single extended information processing (distributed cognition) system. The system in our study comprises the people, space and artefacts involved in the two RP meetings observed.

In line with other DC researchers, we have utilized a specific DC framework, Distributed Cognition for Teamwork (DiCoT) [17], to guide what aspects of ARE work activities to focus on for the DC analysis as well as to provide a systematic approach to data collection and analysis. DiCoT was first described and applied in [17] to study the teamwork in the London Ambulance Service. Application of the DiCoT framework and its set of 18 cognitive principles and three themes has enabled us to describe three main areas of cognition involved in this area of ARE, as well as explain the efficacy and limitations of the observed ARE process in terms of the cognitive significance of particular people, artefacts, the work place and their interactions. The contributions of this study are twofold: (1) the first and novel application of DC and the DiCoT framework to analyze aspects of the collaborative ARE process is a contribution to RE research and practice, (2) the utility of DiCoT in the context of requirements engineering is a methodological contribution to DC research.

2 Background

Distributed Cognition (DC) is a theoretical and methodological framework [23] that describes an approach for studying the organization of cognition in collaborative group activities. In this framework, cognition is viewed as a system capability, extending beyond individual brains into the interaction between individuals in the group as well as interactions with artifacts and structure in the work environment as cognitive resources. This view is based on the observation that groups have cognitive properties that cannot be explained by simply aggregating the cognitive properties of the individuals in the group. The functional system, then, is the cognitive unit of analysis, where this system has cognitive properties different to the sum of the people in the system and solves cognitive problems differently to individuals [24]. In our case, the functional system is the people at the ARE meeting, artefacts used in the meeting, as well as characteristics of

the room that may support or hinder the distributed cognition related to achieving the functional goal. The functional goal being the agreement on a priority order for working on the user stories presented.

Unlike the traditional view of cognition as symbol manipulation inside the heads of individuals, the distributed cognition is observable since the "computation" is the flow and transformation of information between the elements of the functional system ("*the propagation of representational states across representational media*" [23]). In this view, artifacts and structure in the workplace appropriated in the performance of work are more than *"mere stimuli for a disembodied cognitive system"* [18].

In the DC the emphasis is on uncovering the dynamics of how knowledge is propagated and transformed through the functional system by describing the subtasks and interactions at a high level of detail, identifying breakdowns and accomplishments in the functional system. Rogers [3] describes the initial approach as a *"micro-level analysis"* that distinguishes the flows of representational states by describing *"in increasing detail the seemingly trivial and the usually taken for granted aspects of actions and interactions."* Vaesen [25] describes this analysis as reverse engineering in the sense that the task is to *"derive and model the system's information-transforming subfunctions and the particular ways in which these are organized so as to realize the system's functional goal"*.

There are a number of possible levels of activity and cognitive perspectives a DC analysis could focus on when observing and analyzing a work activity: communication dynamics between people; information filtering or biases; collaborative manipulation of an artefact; and appropriation of structure to simplify information sharing, collective memory, or lessen the cognitive load on individuals. The DiCoT framework [17] provides a checklist of 28 DC principles to consider for a DC analysis of a collaborative team activity. The authors of [17] base the principles on their synthesis of those found in DC literature. In DiCoT, the principles are grouped into five broad themes, each of which represents a particular emphasis with which to view and analyze the collected data in multiple passes. The three themes reported in this paper are: (1) information flow (2) physical layout and (3) artifact details. The other two themes, related to social structure and temporal considerations, are also relevant to the overall study and will be reported in a later paper. DiCoT's tabular and diagrammatic approach to data collection and analysis was loosely followed in the field notes and were supplemented by content and interaction analyses of electronic recordings of meetings and their transcripts.

The information flow theme focuses on identifying what information flows and transformations are important to the ARE activity. Questions to be addressed include: What information is significant to whom for what purpose? What structures broadcast information relevant to the activities (information radiators), as a coordinating mechanism? What structures act as buffers to information flow to avoid constant interruptions to work from new information? What is limiting access to relevant information? What structures or activities are important for information coming together to make decisions (information hubs)?

The physical layout perspective considers the role of space, spatial structure and the arrangement of material objects in the workplace in supporting cognition and includes the possible role of physical bodily support (e.g. pointing). Mechanisms for how people

are kept informed of what the current activity is, and what is planned, are considered (situational awareness), as well as limitations of the horizon of observation of group members. The focus of the physical layout perspective is to address the question of how well the physical layout of the workspace supports information flows and processing and whether it could be improved.

3 Research Design and Implementation

The main aim of this research was to understand the distributed cognition involved in the ARE process in practice. Two meetings aimed at prioritizing user stories in the early requirements phase of an Agile project were selected as examples of the ARE process. A DC analysis of the process begins with identifying the high-level cognition and functional sub-goals in the process, as well as the enabling information flows and transformations (RQ1). This cognitive description of the process is then analyzed using the principles from three themes from the DiCoT framework previously discussed (RQ2). Principles from DiCoT that are identified as being adhered to in the meetings provide a theoretical foundation for explaining the efficacy of the RE activities taking place in the meetings.

The two research questions we sought to answer, aligning with this approach, are:

RQ 1 What aspects of the of observed ARE process are cognitively significant?
RQ2 What principles from DiCoT are important in the observed ARE process?

The data for the DC analysis were gathered by observing two requirements prioritization meetings of an Agile product development project. The meetings occurred early in the project, before development had started, and involved a group of stakeholders collaboratively prioritizing sets of user stories, one at a time. The data collected comprised observational data (photographs of the workspace and copies of some artefacts), field notes and transcripts of audio recordings of the two meetings. The data were gathered by the first author as a non-intrusive observer. A qualitative analysis tool (NVivo) was used to support the analysis of the meeting transcripts. The field notes captured aspects of the ARE process being observed. The focus during data collection was to observe and note the immediate impressions of the cognition occurring in use of space, artefacts and people, based on researcher's understanding of DC theory. The field notes were time stamped periodically to enable easy cross-referencing with the audio transcripts, which were also time stamped.

Most of the DiCoT analysis was done after the meetings, based on a synthesis of photographs, field notes and the meeting transcripts. To answer RQ1, the data analysis involved reviewing the field notes and coding and categorizing snippets of the transcripts as different types of information being sought, challenged or shared. These types of information were then coded and grouped according to: (1) the purpose of the information (expected cognitive outcome or goal); and (2) an area of cognitive effort. For example, in one transcript the sales manager proposed that a specific user story be given high priority because she was losing sales as a result of its absence in the product line. This information was coded as relating to "requirements business value" (rather than "requirements meaning" for example). It was grouped in the general area of cognitive

effort that related to "reasoning about the absolute value of a requirement", with the cognitive goal of "understanding multiple perspectives".

Answering RQ2 involved analysis of the photographs, field notes or coded sections of the meeting transcripts as suited the information sought for each DiCoT principle. For example, the information radiator principle from DiCoT was analyzed based on data from the transcripts – what information sources did team members refer to often; as observation in the field notes– what information sources were noted as being referred to frequently; as well as photographs of the information sources available easily around the room. The areas of the transcript to focus on were guided by the field notes which identified interactions of cognitive significance. On the other hand, descriptions of the perceptual principle and naturalness principle, for example, were based on photographs of the workplace and researcher's memory, reminded by re-reading parts of the transcripts and field notes.

4 The Context of the Field Work

The field work was conducted in a medium-sized organization in New Zealand in the Finance/Insurance sector with around 200 employees and 10 agile development teams. The organization represents the relatively common situation of an in-house software development department that uses agile development methods with a mixture of practices from Scrum and Extreme Programming. The software development project studied involved developing functionality for both internal and external clients.

The two observed RP meetings (P1 and P2) were one-hour long each, three days apart with the same participants and a very similar format. They took place during the early requirements phase of the project, prior to development starting but had 75 user stories in the product backlog (PB), some already prioritized. The functional goal of these meetings was to agree on the rough order of the large pieces of work (groups of functionally related requirements)to be done (one or more iterations each), and then order enough of the more valuable work for the development team to estimate and plan the first few sprints. Present at both meetings were two business analysts (BA1 and BA2), a Project Manager (PM), the Product Owner (PO), a Customer Services representative (CS), and the Sales Manager (SM). BA1 facilitated both prioritization meetings, set the room up and managed the sequencing of the activities in the meetings. The other members of the core development team (two testers and two developers) were not present at these meetings because they were still finishing off other projects.

In terms of the physical environment, the meetings took place in a meeting room with everyone sitting around a table. The significant cognitive artefacts were the whiteboard, the user story cards and the projected computer screen, which all acted as information radiators, filters and transformers, as described in the DiCoT framework, at different times.

5 Results of the Distributed Cognition Analysis

In this section the process is analyzed in terms of the significant cognitive goals (RQ1) and then the analysis using the DiCoT framework is presented (RQ2).

5.1 RQ 1: What Aspects of the Observed ARE Process Are Cognitively Significant?

The RP process observed involved repeatedly selecting an unprioritized user story and deciding on its position in the previously ordered part of the PB. Based on analyses of the transcripts and field notes of the meetings, three aspects the RP process that are cognitively significant can be distinguished: (C1) explain and reason about stakeholders' perspectives on the value of that user story; (C2) agree on a position for the user story in the ordered part of the PB; (C3) reasoning, questioning and explaining the meaning of user stories in order to develop (or confirm) a shared understanding of the meaning and context of the user story. For (C1), divergent thinking was prevalent, with different perspectives and information about the value of a user story being sought from team members. The type of cognition in (C2) was more convergent thinking, aiming to get consensus on the priority of the user story being discussed. The information sharing and cognition in (C3) were about verifying shared understanding of relevant user stories, mainly through question and answer interactions and re-statement of others' explanations. A summary of the important information processed and the cognitive outcomes for each area of cognitive effort is presented in Table 1.

Table 1. Analysis of each area cognitive effort in the observed process

Area of cognitive effort	Important information shared and processed	Cognitive outcomes
(C1) Reasoning about the absolute and relative value of the user story	- The high-level functional area or part of the wider product the requirement relates to - The main prioritization criteria - Which prioritization criteria are currently being applied - The value of other user stories as previously discussed	- Shared understanding of different perspectives on the value of the user story - Shared understanding of some explicit and tacit criteria for reasoning about the level of importance of a user story
(C2) Agreeing on the relative priority of the user requirement	- Previous decisions about priority of other user stories - Others' points of view on priority order - Which prioritization criteria are currently being applied - Current proposed priority and changes/alternative proposals	- Consensus on the priority position of the user story in relation to other ordered user stories
(C3) Reasoning about the meaning (functionality) of the user story	-The user story feature, the user type it is for and the expected value to the user -Domain knowledge about the current process relevant to the requirement -Domain knowledge about the expected change from the use of the proposed feature - The dependencies of the requirement on other requirements or vice versa	-Shared understanding of meaning of user requirement. Development of a Team Mental Model -Further development of a shared language -Uncovering tacit assumptions or misunderstandings about a user story

5.2 RQ 2: What Principles from DiCoT Are Important in the Observed ARE Process?

Having understood the main cognition in the RP process, this is then analyzed from a DC perspective using the DiCoT framework in the next section. Each DiCoT principle within the three DiCoT themes is described based on analysis of the data collected and the conceptualization of the cognition in the RP process.

Principles for the "Information Flows" Theme

Information Movement. The mechanics of information moving around the cognitive system (e.g. physical, verbal). Information movement is dense in the RP process, as identified in the second column of Table 1. This movement involves many information channels, including between individuals and other group members (verbal and visual); the writing on the whiteboard (visual and physical); the spatial arrangement of cards (visual and physical); the writing on story cards (visual); the contents of the projected screen ((visual, physical). This highlights the cognitive complexity of the interactions and information flows, which are coordinated and simplified through the use of the physical story cards complemented by the electronic versions.

Information Transformation. Transformation of information from one representational form to another. One key and directly observable information transformation was the transformation of the user story priority and value information in individual's minds (evidenced by what they said) to the visual spatial information (order) of user stories on the whiteboard or table. Conversely, this visual spatial information was transformed into information in people's minds for processing (e.g. verifying their view of what was agreed on, or challenging/strengthening their mental model of the situation). Also, the visual spatial information of story cards acted as an information filter to focus on order or categories and not on the written details of a user story. The meeting facilitator often acted as an information filter, transforming others' spoken views of value into a synthesized view or proposing a specific view as strongest. She was skilled at this and also had a certain power advantage as meeting facilitator, so her information filtering was often "deferred" to.

Information Hubs. Different information channels meet and information sources are processed together. Within the meeting the whiteboard with the spatial arrangement of story cards and writing was the central and most-used information hub. It brought together the information and information processing from individuals and previous prioritization work.

Buffering. New information is stored until an appropriate time to avoid interfering with the task at hand. Information buffers were important at different times in the meeting to avoid interruptions, but not lose the interrupting information. For example, the whiteboard was used as an information buffer. If information was needed about a requirement or its value, future information gathering task was noted on the whiteboard (and perhaps the relevant user story card) and the prioritization process continued with minimal interruption. The spatial arrangement of story cards could also act as a buffer. If a new idea came up about a user story other than the one being worked on, often this user story card would be put to one side spatially as a reminder to come back to it.

Communication Bandwidth. Face to face communications is richer than other means (exchanges more information). The face-to-face and co-located information channels were high bandwidth in their richness of visual and verbal interactions.

Behavioral Trigger Factors. Individuals respond to local factors rather than an overall plan. The start and end of the cognitive activities were generally signaled by a behavioral trigger from an individual team member, generally the meeting facilitator. The move to agreeing on the priority of a user story was generally signaled by the behavioral trigger of someone proposing the position of the user story being discussed, and this was either accepted or resulted in further discussion about value and possibly a counterproposal. The facilitator was central to the triggering a change in focus and achieving consensus through behavioral triggers and summarizing others' views and the prevailing accepted views. Sometimes there was no clear cognitive trigger to end some discussions about a requirement since sufficiency is uncertain (more time may uncover unknown unknowns, misunderstandings, or hidden assumptions to test). Often the facilitator would propose ending the discussion about a particular user story based on time urgency and others assented by silence.

Principles for the "Use of Space" Theme

Space and Cognition. The use of space to support cognition such as problem solving. The spatial arrangement of physical story cards is a visual information channel to convey functional relationships of requirements, priority order, previous decisions and understanding, and the requirement with attention. This was the key mediating artefact throughout the prioritization process and provided diverse cognitive support throughout the process. This approach to RP would have been cognitively much harder without physical cards to rearrange, and act as a dynamic, in-the-moment information radiator and visual "memory" of priority.

Perceptual Principle. The use of spatial representations with clear mapping of spatial layout to what is being represented. Physical manipulation of story cards simplified the cognition of proposing and testing a priority position or functional relationship of a requirements with other requirements. There was a clear mapping between the spatial distance and order of cards and the functional distance and priority order of requirements. This manipulation was cognitively important to the prioritization process, particularly during consensus development.

Naturalness Principle. The form of representation matches the properties of that being represented. The small size of a story card constrains the amount of detail about a user story that is documented, supporting its use as a reminder to have a conversation about the meaning and value of the user story when it is needed. The cognitive significance of this was – cards small enough to be manipulated but still readable (within the horizon of observation) of everyone – just enough info to need discussion.

Subtle Bodily Supports. The use of body movements for cognition (e.g. pointing). Pointing at user story cards or lifting them off the white board and raising them in the air was a common way for the facilitator to draw the group's attention, emphasize a point, or

support a behavioral trigger to change tasks. Cognitively this may seem unimportant, but in fact it was a key mechanism to keep the group on-task, where there were potentially many information sources to distract them. Non-verbal information exchange through body language was rich and significant in the meetings. This included nodding and head shaking, eye contact, pointing and hand gestures. Example of information conveyed are agreement, disagreement, strength of conviction, attention or loss of it. It was clear that such visual cues were important cognitively as feedback and attention information for this group of people doing work together. This strengthens the argument for face-to-face meetings for this process.

Situation Awareness. Team members are aware of what has happened, is happening and what is planned. The user story cards on the whiteboard provided situational awareness because they were an information radiator of the current situation: what has been prioritized, what still needs to be prioritized, what is being proposed and what user story currently has attention. Sometimes the table was used to draw attention to a sub-set of user stories to manipulate and decide on priority order. This illustrates the diversity of the cognitive benefits of using physical user story cards in this way.

Horizon of Observation What Can be Seen and Heard by Team Members. The layout of the room as well designed to allow the main sources of information and information processing, other team members and the main artefacts, to be within the horizon of observation of everyone in the meeting without much effort or movement. Cognitively, this meant that the exchange of information was low effort and attention could be redirected easily.

Arrangement of Equipment. The effects of the physical layout of the workspace on information flows. The channels of information flow were not inhibited by the arrangement of equipment. The availability of the projected spreadsheet of user stories was important cognitively to the effectiveness of the meeting by providing a fast search mechanism for user stories.

Principles for the "Artefact" Theme

Mediating Artefacts. Artefacts that the team bring into coordination to complete their task. The user story cards on the whiteboard were the central mediating artefact for the cognitive effort in the process. The user story cards were brought into coordination (order) to complete the task of prioritization consensus. The order of other story cards also indicated the state of previous priority decisions. The story cards also coordinated the group's decisions and attention on a proposed priority order or changes to a proposal, for discussion and agreement or a counterproposal.

Creating Scaffolding. Team members appropriate parts of their environment as to simplify a task. The movement of user story cards on the whiteboard and table is an example of "external scaffolding to simplify our cognitive tasks". As previously discussed, the transformation of individual's mental cognition to visual cognition simplified the coordination of.

Representation-Goal Parity. An artefact explicitly represents the relationship between the current state and the goals state. The spatial arrangement of story cards closely represents a current state of unprioritized user stories (spatially separate) and the goal state of prioritized user stories (the card in the ordered column).

Coordination of Resources. Abstract information structures can be coordinated to support action or cognition (e.g. a plan or a goal). The pre-arrangement of the spatial arrangement of the user stories on the whiteboard was cognitively significant as an information radiator of what prioritization had been done and what needed to be done, giving the meeting a clear plan and goal. This information was updated as the story cards were moved around on the whiteboard, providing information about progress towards the goal and sometimes triggering a new plan for the meeting.

6 Discussion

Overall, analyzing this ARE activity through the lens of DC has highlighted the cognitive complexity of the process in terms of information sharing and processing, as well as information seeking and retrieval. The DiCoT analysis has provided a structure to analyze the web of interactions between the group members, the mediating artefacts and the workspace layout. The analysis has provided evidence to explain the strengths and weaknesses of this process from a cognitive perspective and evidenced the cognitive significance of aspects of the workspace, information flows and artefacts.

6.1 The Observed Agile Requirements Prioritization Process: A High-Level View

The observed ARP process cannot be characterized as a single named prioritization technique identified in the review by ([21] Fig. 5, p. 572). The observed process did not follow a predictable structure with clear prioritization criteria and did not have specific roles and information sources pre-planned. This aligns with the findings of [1] in their interview-based case study which found that the "*prioritization process itself varies significantly in terms of participants involved, prioritization criteria applied, purpose and frequency of the prioritization*". Despite the observation that the process was cognitively complex and unpredictable, it was effective: the functional goal was achieved. The DC analysis provides an explanation of this success, suggesting that it can be attributed to the good use of space and artefacts and the diversity of participants as a distributed cognitive system to achieve this goal.

The ARP process conceptualized in a number of other papers (e.g. [1, 26, 27]) is generally broader in scope and level and does not consider the level of detail in specific RP meetings that our study has. Our study complements these models by focusing on this detailed process as well as considering *early* prioritization meetings. These early meetings are important because they lay the foundation for subsequent meetings in terms of planning (e.g. release goals and order of work), initial scope, stakeholder involvement, and the ARP process itself.

6.2 The Cognitive Role of the Prioritization Criteria

It can reasonably be expected that shared understanding of requirements and application of the prioritization criteria would be central to the RP process. The Scrum framework does not specify particular criteria to evaluate the value of PB items to order the PB, so it useful to see what happens in practice, with six different value criteria identified in this study: (PC1) the strategic value (to the case organization) of the requirement or its product functional area; (PC2) the strategic and operational value to the current or potential end-users; (PC3) the negative impact of not implementing the requirement; (PC4) the cost/effort versus the benefits of developing and deploying the requirement; (PC5) risk of negative impact on internal stakeholder with dependencies on changes related to the requirement; (PC6) the potential negative impact of dependencies between this requirement and others. Different team members tended to be biased towards the application of specific criteria For example, the PO (a manager also) tended to apply PC1 ("*this is part of a strategic initiative*") and PC4 ("*it's cheaper to keep doing this manually than spending 5 sprints on it*") when discussing priority. The sales manager SM ("*we are losing sales without this*"), BA3 ("*at installation the customer is surprised it can't do this*") and CS1 ("*this is the most common feature request I get -, it's highest priority*") often invoked PC2 and PC3. BA1 had the clearest "big picture" and would often bring up PC5 ("*we should check if this change will have a big impact on the BI people*") and PC6 ("*If we do [this] then we have to send out comms quickly to all affected [customers]*"). These prioritization criteria have some overlap to those found in [26] in their multiple case study of agile requirements prioritization. While we found business value (PC1 and PC2), negative value (PC4), risk (PC5) and (limited) developer input were discussed in our study, project context, estimated size, external change and learning experiences were not involved in our ARP process. This may highlight some differences between early and later ARP meetings, but this needs more research. It will almost certainly be a function of the roles and value biases of those present. The criteria were often tacitly assumed and applied in a fairly ad hoc manner in the observed meetings. This could be an area of possible improvement: a mechanism to encourage explicit cognitive effort in developing shared understanding of the prioritization criteria and an associated information radiator.

6.3 The Cognitive Role of the User Story Cards

The DiCoT analysis provides a compelling argument, at least from a DC perspective, for the use of physical story cards and their spatial manipulation in RP. The DiCoT analysis shows that the story cards feature in almost all areas of DC and provide substantial cognitive benefit as information radiators, information buffers, information filters, information transformers, and attention coordinators. Importantly, the cards afford a significant cognitive load transfer from individual memory of priority to visual perception of order. Moreover, they were used by the facilitator in behavioral triggers to manage the flow of the work in the meeting, as well an information radiator for the meeting plan and progress. Transferring the cards to the development team's work board, in order, also served as a memory of the outcome of the process and an information radiator for others

not at the meeting. As a cognitive artefact the user story cards could be used at different levels of cognition: reading the text, use of the label or manipulated as a card. The characteristics of the user story cards were well suited to the RP process: they were well sized to manipulate and carry around, yet still be read easily; they had sufficient requirements detail to act a reminder but encourage discussion; the information on the cards was useful for the process. The availability of the searchable spreadsheet of user stories complemented the story cards, although was not used often.

6.4 The Important Cognitive Role of the Meeting Facilitator

The DiCoT analysis highlighted the cognitive importance of a skilled facilitator in the process. The facilitator played a central role in information movement, filtering and processing. This can be both a strength and a weakness: the effectiveness of the process relied on the cognitive skills of the facilitator. In addition, the facilitator had more influence than others in the meeting in terms of the information filtering and flow of the meeting (changing the group's attention), because of the power attributed to the facilitator role.

6.5 The Importance of the Face-to-Face Meeting as an Information Hub

From a DC perspective the meetings can be conceptualized as an important information hub in the requirements management process. The meetings were a central focus where many information channels coincided. This information was processed by the group to make a decision about the requirements priority order. Without this meeting involving a diversity of stakeholders' perspectives it would have been difficult to achieve such high-quality decisions about the priority. The face-to-face interactions provided rich and immediate information communication channels (including non-verbal). In addition, the visual cognitive affordance of *physical* manipulation of user story cards would be difficult if the group were not co-located.

6.6 The Importance of the Room Layout

The DiCoT analysis identified that the room was well laid out for the cognition involved in the ARE process. The room was laid out so that important information sources (people and artefacts) were within everyone's horizon of observation and information flows were low effort. It is worth noting that the room was sufficiently isolated from outside to avoid distracting information unrelated to the meeting.

6.7 The Need for a Diversity of Perspectives on User Story Value

ARE promotes consideration of multiple stakeholders' views in the prioritization process and to some extent the DiCoT analysis justifies this. The broader perspectives of value and meaning for user stories resulted in decisions about priority that were better informed and benefited from the expanded cognitive base. For example, one set of user stories (previously a high priority), was discarded and another became high priority

unexpectedly based on the views and arguments of some team members influencing those of others. This effect of diverse perspectives on team decision-making has a strong theoretical basis (e.g. [28]).

6.8 Secondary Cognitive Outcomes of the RP Process

The DC analysis has identified some significant cognitive outcomes of these early ARE meetings process, apart from the prioritized user stories, that were important in later collaborative requirements work. These include: a significant deepening of the shared understanding of some user stories; a broader view of requirements value from others' perspectives and criteria to judge value; significant development of shared language for the team to discuss, explain and reason about requirements; shared understanding and embedding of a collaborative process for RP.

7 Reflections on the Application of DiCoT

This study has demonstrated the usefulness of using the DiCoT framework to perform a DC analysis of collaborative work in ARE process. The analysis has provided a rich set of insights as a basis for understanding the strengths and weaknesses of the ARE process and reasoning about possible changes. However, the effort in collecting and analyzing the data was significant and may not be feasible to be conducted regularly. The framework itself was reasonably straightforward to apply with clear descriptions of the DiCoT principles. However, the themes were intertwined and sometimes it was difficult to know how to differentiate the artefact view and the information processing view. Starting the DiCoT analysis with a high-level cognitive description of the ARP process was needed to inform the DiCoT description.

This study suggests that the themes and principles of DiCoT could be used as a checklist to assess an ARE activity, the artefacts involved and the layout of the workspace. For example, the physical layout of the room can be checked as being suitable for smooth information movement between people, and to and from the significant artefacts. The horizon of observation can be checked as being suitable to provide situational awareness. This same approach of DiCoT could be used as an assessment tool if the RE process does not appear to be going well.

The DiCoT framework can also be used to reason about changes or redesign of the RE process. For example, it is common to have the user stories stored electronically. Given the understanding of the cognitive affordance of physical story cards, the positive and negative cognitive impact of replacing them with electronic versions of user stories, at least in the RP process, can be identified. Another common change to the RE process to consider is the situation where group members are geographically distributed and communicating electronically in real time.

8 Threats to Validity

Although it is not possible to cover every contextual factor in this study, we did take some steps to ensure internal validity. We used data triangulation between the two meetings

throughout data analysis. To ensure continuity of data collection, all field work was conducted by the first author. It is possible that selection is a threat since the team was selected by one contact, although invitations were sent more widely. External validity is low and we cannot claim the results will apply to all Agile projects and teams, however, our aim was to uncover some useful insights that may resonate with other practitioners. DiCoT analysis of the ARP in different contexts to broaden the likely applicability is for future research.

The presence of the researcher in the meetings may have reduced reliability by changing the behavior of those being observed. To address this the observing researcher spent some time with the team prior to data collection and gained their trust and a degree of comfort with the researcher's presence in meetings. The meetings were transcribed word for word and the observing researcher identified the speakers. We discussed the resulting analysis with some team members. We tried to adhere to the explanations and structure of DiCoT in the original paper by Blandford and Furniss [17] closely but inevitably we may have made some subjective assumptions in doing this.

9 Conclusion

The novel application of DC theory through the use of DiCoT to the requirements prioritization as part of an ARE process has provided an empirically evidenced explanation of why this way of implementing the RP process was effective. In answering RQ1, three main areas of cognition were identified in the process. In addition, some insights were gained about the different perspectives on requirements value associated with different roles, as well as the six prioritization criteria applied. Application of the DioCoT framework (RQ2) also identified a number of aspects of the process that had cognitive significance to its success. For example, the DiCoT analysis provided substantial evidence that the use of physical story cards, a skilled facilitator, and a cognitive-friendly work environment were central to the success of this approach. This may provide a basis for others to design, modify and assess other activities in the ARE process.

Future work planned includes the extension of the DiCoT analysis to include the two DiCoT themes not included in this study and applying DiCoT analyses in other contexts. Also, the application of DiCoT to other Requirements Engineering activities will be explored.

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