An Actionable Approach to Understand Group Experience in Complex, Multi-surface Spaces

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ABSTRACT
There is a steadily growing interest in the design of spaces in which multiple interactive surfaces are present and, in turn, in understanding their role in group activity. However, authentic activities in these multi-surface spaces can be complex. Groups commonly use digital and non-digital artefacts, tools and resources, in varied ways depending on their specific social and epistemic goals. Thus, designing for collaboration in such spaces can be very challenging. Importantly, there is still a lack of agreement on how to approach the analysis of groups’ experiences in these heterogeneous spaces. This paper presents an actionable approach that aims to address the complexity of understanding multi-user multi-surface systems. We provide a structure for applying different analytical tools in terms of four closely related dimensions of user activity: the setting, the tasks, the people and the runtime co-configuration. The applicability of our approach is illustrated with six types of analysis of group activity in a multi-surface design studio.

Author Keywords
multi-surface; ubicomp ecologies; horizontal display; shared-display; groupware; collocated collaboration

ACM Classification Keywords
D.2.10 Design; H.5.2 User Interfaces; J.4: Social and Behavioral Sciences

INTRODUCTION
Interactive surfaces have become a key part of everyday life for many of us. Mobile-handheld devices are now widespread and large interactive screens are becoming more accessible and pervasive [57]. People commonly interact using a heterogeneous ecology of tools and resources, both digital and material. So there is a steadily growing interest in the design of spaces in which multiple interactive surfaces can be used concurrently [1] and also in understanding their role in collaborative activity [11]. The affordances of multi-surface spaces have been explored in a wide range of contexts such as design (e.g. [55]), data exploration (see [1] for a review), simulation (e.g. [43]), cooperative group work (e.g. [52]) and learning (e.g. [27]). A driver of this work is to help address group activity where multiple people interact with multiple devices (*-*) which is more complex than single-user interfaces (1-1) or multiple people interacting at a shared device (*-1). In such multi-surface environments, the heterogeneous ecology extends beyond the devices and user interfaces, to the materials, the multiple roles that are adopted in relation to the task, the tools, or the group process. Analysis of such an ecology is challenging, especially given that the technology can be partly or fully unintegrated.

There is a substantial body of research on understanding how people collaborate with single display groupware [57] but there has been little agreement on approaches to the analysis of situations in which multiple devices are used by groups in an interactive space. User experience evaluations offer an important class of tool. However, most are targeted at single users [5], and provide little information about a range of elements that are likely to shape user activity. Observational studies and user interface evaluations sometimes ignore the setting, tasks or roles within the unfolding group activity, and so often oversimplify the relationships between them. There is a need for multi-method approaches for analysing group activity - what people actually do in these spaces - as a whole and that can capture the complexity of group activity in heterogeneous multi-surface spaces.

In short, analysis and understanding of user activity in multi-surface interactive spaces is challenging, especially if it properly acknowledges the complexity of activities involving multiple users interacting with multiple surfaces, blending heterogeneous tools, resources, work roles and rules, to tackle complicated knowledge-rich tasks.
The CSCW, and HCI communities have recognised the opportunities, technical challenges and problems with interactive multi-surface and multi-device ecologies [1, 3, 11, 52]. However, they have also acknowledged the lack of understanding of the challenges faced in facilitating effective collaboration – which depends, in turn, on understanding the activity of groups using multiple devices and interactive surfaces [8, 11], especially in complex work domains and when deployed in real world contexts. It is timely to develop methods and theoretical frameworks that can facilitate a systematic analysis to identify the problems and possibilities of current use, and the impact of the integration of new technologies (such as interactive surfaces) for increasingly complex user activity in heterogeneous ecologies of devices. The contribution of this paper is the formulation of an actionable approach to support the selection of available analytical tools and the interpretation of results, to cover four closely related dimensions of group activity: the setting where the activity unfolds, the tasks being tackled, the roles adopted by the people involved and the co-configuration of the intended design in runtime.

The approach is targeted to designers and researchers to document and tease apart the many dimensions of group activity - and enable them to gain insights into elements of the system (the ecology of devices, the social interactions and the task itself) that work well, and those that seem to pose difficulties. Norman [36] observed that a key feature that distinguishes an activity-centred approach from others (e.g. user-centred) is that it requires both a deep understanding of users, and also of the technology, the tools, and the context of the activities. Thus, an activity-centred approach provides a better fit to understanding group activity in multi-surface spaces, as a whole. Our approach is grounded in an activity-centred framework which offers a holistic perspective on what people actually do in group activity, and the tools, resources and social interactions that become bound up in that activity [10]. The application of this framework can also help bridge theoretical models that explain collaborative activity with specific HCI analysis techniques, particularly if those theories are abstract and not directly actionable. We illustrate our approach in action by analysing group activity in a multi-surface design studio. The illustrative case study includes the application of multiple methods to investigate: (i) user experience, (ii) tools usage, (iii) users’ attention, (iv) space usage, (v) roles and (vi) the processes involved in completing the task.

The rest of the paper is organised as follows. The next section provides an overview of selected multi-surface spaces and methods available to analyse collaboration, mostly used with single display groupware. Then, we present the principles underpinning our approach. After this, we describe the study that illustrates how the approach can be put into action. This includes sets of analyses, which, when combined, provide insights into the unfolding group activity of four teams within our multi-surface studio. We conclude with a discussion of the application of our approach and ideas for future research.

RELATED WORK

State of the Art: Complex Surface Systems

The widespread proliferation of surface devices in the workplace, learning settings and everyday activities, has moved us towards a world where computers begin to ‘disappear’ - cognitively and emotionally [45]. If the cognitive and emotional ‘load’ around the use of devices disappears, then groups can focus more on interactions with information, communication of their ideas and cooperation with other people [53]. Since the development of the first spaces that distributed information and functions across multiple screens and devices (e.g. [45, 46]), there has been a steadily increasing interest in the design of complex multi-surface systems. One of the most relevant and highly referenced of these systems is Wespace [52]. This supported small group exploration of information, featuring multiple shared displays and personal computers. The highlight of this study was that it addressed the complexity of analysing group work in a realistic scenario by combining ethnographic methods (e.g. observations of patterns of usage) with logged interaction data and explicit feedback from users. Multi-surface spaces have also been attractive in educational contexts [16]. A variety of tabletop and tablet-based classroom ecologies have been designed to support teacher’s orchestration of small-group tasks [27].

More recent research on multi-surface spaces have focused on the integration of various devices into a central system. This facilitates the distribution of information among users. Reticular Spaces [3] proposed the unification of the UI of heterogeneous interfaces for organising information and providing accessibility to both collocated and remote users. Shared Substance [17] followed a data-centred (rather than an activity-centred) approach to inform the design of a multi-surface environment used in areas that require groups of users to explore and interact with heterogeneous content. Activity Space [23] allowed the integration of several devices (a tabletop, tablets and laptops) into a physical workplace by offering three related but de-coupled layers, which contain: the devices, activity management functions and resources. The Huddle Lamp [38] allowed the use of gestures across mobile devices, and adapting the role of devices based on their detected orientation or distance from other devices. Finally, VisPorter [12] allowed access to multiple perspectives on visual information in various displays (tablets, a vertical display and a tilted tabletop).

Most of the examples mentioned above reflect the current focus on improving the technology to provide enriched experiences in multi-surface spaces. However, there is still a need to develop conceptual tools to better understand why some things work well, while others fail, by going beyond these individual explorations, especially when different technologies are used in realistic, heterogeneous settings.
Current Methods to Study Group Work in Interactive Surface-based Settings

There has been a proliferation of studies exploring group interaction in multi-surface environments. We now list some examples that show the diversity of methods used in multi-device spaces and to understand group work mediated by interactive surface groupware. Ethnographic methods in HCI and CSCW [6] have been used to observe extensively and in detail the design, development and/or usage of technologies in particular settings (e.g. [4, 21]). This has included the exploration of complex group activity in multi-device and/or multi-display spaces (e.g. [9, 13, 28, 29, 52]). Attempts have also been made to extend usability tests, originally aimed at single users, to provide information about group experiences in a multi-user system [5]. The evaluation of a multi-surface system has been linked to measures of task performance [43]. The analysis of human mobility and proxemic relationships have also been used to analyse and support cross-device interactions in multi-device environments [30].

There have been several studies analysing group work primarily in single surface settings (e.g. multi-touch tabletops). For example, Tang et al. [50] applied multiple methods of analysis that considered the arrangement of people around a tabletop and even the impact of social scaffolding (e.g. suggesting roles to users). Davis et al. [14] conducted interaction video-analysis to discover patterns of collaboration in a tabletop-based museum exhibit. Ryall et al. [41] explored how group and display size can affect the task and strategies of groups interacting at a tabletop.

Most of the studies mentioned above evaluate their systems or analyse group activity using widely varied approaches. An overview of other methods used to study collaborative activity can be found in [42]. However, as some methods commonly focus on responding to very specific research questions, they can miss the bigger picture, and alternative key elements that may shape a group’s activity.

**APPROACH**

Our approach is grounded on the principle that group activity is not only shaped by the design of the tools or technology, but by the loosely-coupled relationship between the many tools available, users, tasks and the activity of people during runtime, tuning the design. In order to define these aspects of group activity, we use the Activity-Centred Analysis and Design (ACAD) framework [19] at the core of our approach. The ACAD framework, which is informed by research on learning networks and activity theory, can be used to scaffold the selection of specific analysis methods in order to analyse group experience as a whole. These elements are depicted in Figure 1, represented with an increasing abstraction (from top to bottom) in order to understand key aspects of group activity in an interactive multi-surface, multi-device space. These elements are described in detail in the next sections.

![Figure 1. Our actionable approach: the ACAD framework, used to connect specific analysis methods to analyse group activity.](image)

**Theoretical Perspectives on Group Activity**

A variety of theoretical perspectives have been proposed to understand the social aspects of HCI activity. Grounding the design for, and analysis of, group experience in complex multi-surface environments on a theoretical framing can help structure our understanding of individual and collaborative use of technology in relation to collaborative group practice [24]. Examples of these theoretical models include: Design anthropology [20] which is already well-established in CHI and CSCW research – foundational work being done by Bonnie Nardi, Lucy Suchman and others (e.g. [35, 47]). Similarly, the self-improving ecologies approach (e.g. [15]), situates the knowledge for design and improvement within a system, rather than ‘on top’ as some kind of external control. Distributed cognition [22] has been used to analyse and design multi-user systems [39], and, more specifically, for multi-surface learning ecologies [27]. Activity theory [25] has been crucial for understanding technology-mediated activities in HCI because it pays special attention to the integration of artefacts into social practices. Instrumental genesis [37] explains how users cannot be considered as fixed, interchangeable subjects but as entities that evolve as they interact with tools and other people that are also evolving. The work reviewed by Rogers [40] provides a high level differentiation and summary of theory in HCI.

Nevertheless, the recent third wave of HCI research [7] challenges the use of theoretical models to directly explain users’ activity. It demonstrated that pragmatic/cultural-historical approaches, focused on experience, have achieved similar or even better results than theory-driven approaches, especially if those theories are abstract or high level, such as activity theory or distributed cognition. By using the ACAD framework, we aim to achieve a more holistic view of group activity in multi-surface environments. Our approach can provide guidance to select low level analysis methods as well as to provide a way to link these robust theories with the methods of analysis selected.
In addition to the ACAD framework, we also considered alternative frameworks. For example, the activity-based computing (ABC) framework [2] is conceptually close to the ACAD framework in the sense that it decomposes users’ activity into tasks, materials, time, and users. However, the purpose of the ABC framework is to inform the implementation of ‘computational activities’ of a distributed system that ensures adequate synchronisation of data and methods across devices. Another example is the Blended Interaction framework [24]. Informed by embodied cognition theory, it helps to explain the design of user interfaces perceived as ‘natural’. The Blended Interaction framework structures the design space into four sub-spaces: individual and social interaction, the workflow, and the physical space. Authors of this framework observed that connecting the analysis to sound cognitive theories facilitates the interpretation of the empirical observations, potentially leading to more detailed and iterative, but better, designs. We selected the ACAD framework because it provides a holistic view of group activity, focusing on the tasks that the users are given (epistemic), the ways that the users divide up labour (social), and use the various tools, surfaces and materials in the space (set), and how ultimately the design is enacted (co-configuration). Moreover, we illustrate how this conceptual model can be connected with specific HCI analysis techniques to explain group activity.

The ACAD Framework

The ACAD framework has mainly been applied to link design and analysis of complex, group learning situations. The framework considers group activity as emergent and situated. ‘Activity’ here means what people are actually doing, physically and mentally. Activity is socially, epistemically and physically situated. Users’ activity is not directly designable, but other elements (e.g. tools, tasks and work roles), which are also relevant to the understanding of an unfolding group activity, can be designed. Activity is different from task - the prescribed work, or what (officially) should be done, and which can be designed [54]. At runtime, the physical, social and epistemic elements are dynamically entangled together as the group activity unfolds. But at design time, the physical, social and epistemic can be treated as discrete design components. Design needs to pay attention to each of them, even though what is designed and set in place will be reconfigured in use by participants at runtime.

For ease of reference, within the ACAD framework, we refer to the first three components as (1) the set (physical) component – which includes the place in which participants’ activity unfolds, the physical and digital space and objects; the input devices, screens, software, material tools, awareness tools, artefacts, and other resources that need to be available, (2) the social component – which includes the variety of ways in which people might be grouped together (e.g. dyads, trios, groups); scripted roles, divisions of labour, etc, and (3) the epistemic component – which includes both implicit and explicit knowledge-oriented elements that shape the participants’ tasks and working methods. ACAD states that the users’ individual skillsets (e.g. improvisation, argumentation, tool use skills), social relationships (e.g. power relations, working methods, divisions of labour), and even their domain knowledge are not fixed. Rather, they evolve during the collaborative activity, over time. What is designed in advance is then customised, selected from, added to, re-interpreted or otherwise modified by the people involved in the ensuing activity. We refer to this fourth component as (4) co-configuration [19]. This key component may help explain why certain design intentions sometimes do not play as expected in runtime. It can also help understand how some differences among groups of users are not just a function of social circumstances, but also of how information flows around the group, and the choices they make to configure the other three (at least partly) designable components of the ACAD framework.

Actionable Elements: a Range of Analysis Methods

The application of the ACAD framework can help make sense of multiple analyses applied to the same dataset or to provide focus to observations. As stated above, multiple measures of collaboration, interaction, group preferences, usability, tools usage, user experience, task completion etc., have been used to design or demonstrate the effectiveness of multi-user, multi-device systems. Each of these may be automatically, semi-automatically or manually collected in order to provide insights about a specific aspect of groups’ activity. However, having a systemic view of the key components of users’ activity within these spaces requires a conceptual framework that can provide meaning to multiple analysis methods used together.

In calling our approach ‘actionable’ we are taking account of the relationship between the time and resources needed to undertake the analysis and the payoff for design and/or development of the systems. Crucially, our approach (a) can target just key parts of activity in a workflow and (b) can use a more extensive, or conversely a stripped down, toolset to capture different aspects of the activity, depending on time and analytic skills available. This modifiability comes from the layering shown in Figure 1. As this shows, some components are necessary for the approach – such as the core focus on actual activity and the ways of understanding such activity as physically and socially situated. The next section illustrates the application of our approach to analyse and describe group activity in a multi-surface, multi-device space.

ILLUSTRATIVE STUDY

The illustrative case study consists of a series of sessions in the context of group educational design, in a multi-surface design studio. An educational design describes the tasks, materials, pedagogies and social dynamics for teachers and their students aimed at providing learning opportunities in students’ face-to-face or online activities, over a particular time period [18]. As in other areas, such as architecture or
software development, patterns can be used as reusable solutions to commonly occurring educational problems. Educational design patterns can represent learning places (e.g. a lecture room), learning approaches (e.g. building a blog as an educational exercise), or dictate more complex social dynamics (e.g. jigsaw or pyramid) [18]. A pattern language is a structure of these patterns. Educational design is usually performed by teachers themselves, but in a university context, it is also common to find dedicated learning designers [26]. In the next sub-sections we describe the space and the study that illustrate our approach.

**Apparatus: The Design Studio**

The Design Studio is equipped with various digital and physical tools to support the design activity of small teams. Figure 3 illustrates the work area of the Design Studio, featuring four shared digital devices: an interactive tabletop (a), an interactive whiteboard (IWB) (b), a personal computer connected to a projector (c) and a dashboard (d). The Design Studio also features tablet devices (e); a large writeable wall (f); and paper and drawing materials (g). These are all optional tools available to the participants.

For these studies we used a multi-touch collaborative educational design system, the CoCoDes [33]. CoCoDes offers a large multi-touch interface that supports small teams performing early stage conceptual design work on tertiary education courses (see Figure 2, a). CoCoDes is firmly based on educational design patterns and the use of a pattern language (PL) to represent student tasks (b), learning resources (e) or learning spaces (d). CoCoDes provides digital elements that can be manipulated by direct touch (by dragging digital objects and touching buttons), allowing bimanual input and fluid interaction so user-designers can rapidly build multiple candidates of an educational design (f).

By deploying CoCoDes on the interactive tabletop and the IWB (Figure 3, a, b), the same design can be shown in both displays, or two different candidate designs can be shown in each device. This allows users to: i) use the tabletop as the main working device, keeping a high level view on the IWB, ii) split the task so different team members work on two designs in parallel or iii) compare two different designs, each shown in a different device. The user interface provides a flipped timeline where users can arrange patterns on a weekly basis (Figure 2, c). The orientation of all or selected patterns can be rotated 180° when the application is loaded on a tabletop, allowing users to work side-by-side or face-to-face.

Multiple physical keyboards can be attached to the system, to allow fast input by multiple users (three to the tabletop and one to the IWB for our studies). A vision-based touch tracking system [32] links each touch on the tabletop with the user and his/her keyboard’s input.

The shared dashboard (Figure 3, d) shows real-time visual indicators of the candidate designs created using the interactive tabletop or the IWB. These indicators include a list of educational patterns added to each candidate design, a pie chart that shows how a student’s time would be divided among learning spaces (face-to-face and online), and a histogram showing a student’s weekly workload.

**Design: Task, Tools and Roles**

To illustrate our approach we focus our analysis on an open task study of four teams (A, B, C and D), each with three
participants (4 male and 8 female). We recruited the participants through word-of-mouth from the Faculty of Education & Social Work of The University of Sydney. They had various levels of expertise in teaching (4 were advanced, 5 competent and 3 novice teachers) and educational design (5 were advanced and the rest had limited experience), and all knew each other beforehand. All had experience in the Design Studio and at least one member in each team had used CoCoDes before. Eight of the 12 participants had used an interactive tabletop before (touchscreen directories, art exhibits and design projects), seven had used an interactive whiteboard before (mainly smartboards at school), five had used both and all used tablets regularly.

The goal of each team was to produce two high-level competing candidate designs (e.g. the same course based on traditional lectures and/or a blended learning experience) of a 13-week course in the area of Engineering, held at the University of Sydney. Each team member was given one of three possible roles (Lecturer-L, Learning Designer-LD and Quality Assurance Officer-QAO). According to their role, each had specific goals and information about the course. Some goals provided to the participants complemented others’ goals, and some were conflicting. Thus, the task involved the resolution of conflicting information and goals, agreement about the different design versions to be built, compliance with institutional metrics (e.g. a minimum of face-to-face contact between students and instructors), and the construction of the designs using CoCoDes.

All participants were given the following paper materials: a design brief (indicating the requirements and constraints of the course design); and a catalogue of patterns (a pattern language describing relevant patterns for the course). Each team member was provided with a tablet device that included: digital copies of the design brief and the pattern language; and access to the official online system that provides detailed descriptions of university courses. Teams had up to 1-hour to complete the task. After the group activity, a 30-minute semi-structured interview was conducted with each team. Then, each participant completed a questionnaire about their usage of the tools and the space. Sessions were video-recorded and transcribed.

Method

As an illustrative exercise, we apply six methods to investigate: (i) user experience, (ii) tools usage, (iii) users’ attention, (iv) space usage, (v) roles and (vi) the task completion processes. We conceptually grouped the methods around the components of the ACAD framework to respond to three high level research questions that illustrate a variety of aspects of group activity in a multi-surface environment:

Q1: How were the space and the tools used?

Q2: What was the design process each group followed to complete the task?

Q3: What strategies were followed by each group in terms of their social roles and divisions of labour?

Analysis 1 – Tools and space

Q1: How were the space and the tools used?

User experience metrics can provide insights about user satisfaction, usability and accessibility of the tools available in the multi-surface space. To gain insights into the experience of the participants using the CoCoDes interface, they were asked to respond to a usability questionnaire (the UMUX [5], which has four 1-to-7 Likert questionnaire items). Table 1 summarises the results, showing that overall, participants were satisfied with the effectiveness of the system and agreed that it was easy to use (rows 1 and 3). However, three users (from three different groups: A, B and D) found the experience to be somewhat frustrating (row 2). Five team members (the three members of team A and two of Team D) spent too much time correcting things with the system (row 4, responses above 3 in the scale). Overall, although UMUX provides a rapid overview of users’ satisfaction, it does not offer deeper insights into the groups’ experience, or why some tools were used and others not, considering the heterogeneity of the space and the various interfaces available in the Design Studio.

In order to better understand this, we analysed the videos of the sessions, recording the time and duration of each
participant’s interaction with, and attention focused on, each tool, and their location in the physical space of the Design Studio. The use of tools was measured as the effective time when a participant was holding or interacting with a tool and attention was measured as the time a participant spent only focusing their gaze on a tool without interacting physically with it. Figure 4 presents the results of this analysis. Overall, the paper-based course description was used the most (avg: 26%, std: 10), followed by the interactive tabletop (20%, std: 13 use; and 6%, std: 6 attention), the personal computer projected on the wall (12%, std: 6 attention), the tablets (10%, std: 8 use), the IWB (5%, std: 5 use; and 3.3%, std: 2 attention) and the writeable wall (4%, std: 4 use; and 4%, std: 4 attention). Other tools were also occasionally used and often more than one tool was used at the same time.

Results showed that: i) each team used tools in different ways although the task and roles given to users were the same; and ii) participants used the large devices to different extents and in combination with the other personal devices and physical materials available. Thus, the set component was heavily co-configured by the groups in runtime. Each group used a different combination of large devices (IWB, interactive tabletop wall projected computer), smaller devices (tablet, dashboard) and non-digital devices (writeable wall, paper-based print-outs of the course description and pattern language). Team A mainly used only the interactive tabletop, in combination with all the smaller devices available (tablets, the dashboard and the wall projected computer), and the paper course description. Group B also mainly used one large device (the interactive tabletop) as well as the dashboard and the projected computer. Group C and D used both large devices, but different combinations of the other tools. These two teams also wrote on and used the writeable wall. Team C used the dashboard and the projection as well as the paper-based materials. Team D used the dashboard, more than other groups, and the non-digital writeable wall as well as the paper-based materials.

In order to better explain how participants interacted in the physical space, and inspired by the automated analysis of proxemic relationships [30], the location of each participant in the Design Studio was manually recorded and analysed. The data is visualised in Figure 5. In all teams, the participants mostly worked around the interactive table (57%, std: 28 of the total activity time per group member). The remaining time was divided between the space around the regular table (20%, std: 9), the IWB (10%, std: 10) and the writeable wall (12%, std: 12). The four groups did use the space quite differently (Figure 4). Members of Team A primarily worked side by side (sxs) at one edge of the interactive tabletop. In Team B, one team member (blue) worked face-to-face (f2f) with the other two (sxs), as all members moved between the regular table (RT) and the interactive tabletop. Members of Teams C and D positioned themselves in much more varied formations. They used the space around the IWB and the writeable wall. In Team C only one member (blue) worked at the IWB, and the others worked around the regular and interactive tabletop (f2f) and side by side (sxs) by the writeable wall. The use of space in Team D, was more irregular and complex, with all team members moving around and distributing their time working mostly sxs at the tables, the IWB and the wall. All groups reconfigured the location of the chairs and the hand-held tools according to how they worked around the large surface devices.

**Analysis 2 –Design process**

**Q2: What was the design process each group followed to complete the task?**

![Figure 6. Teams’ task workflows. RT=Regular table. IT=Interactive tabletop. Wall=Writeable wall. Coloured circles represent roles as in Figure 4](image-url)

![Figure 5. Space usage: the circles represent the time each user spent in each area of the multi-surface space according to their roles: Lecturer (red), Learning Designer (blue) and Quality Assurance Officer (green). RT=Regular table; IT=interactive tabletop and IWB= Interactive whiteboard wall.](image-url)
All teams were asked to complete the same design task (to build two candidate designs). They were free to choose the tools they would use and the design process was unstructured. In order to better understand the design processes followed by teams to achieve the task, we identified and video-coded four main sub-processes that emerged from users’ activity and that corresponded to the main sub-tasks posed to participants, which included: i) the initial discussion to organise the team work; ii) the negotiation of conflicting objectives; iii) the actual design of the two options; and iv) a meta-analysis comparing both candidate designs. Figure 6 shows the workflow representations of this analysis for each team, illustrating how each team particularly co-configured the epistemic component in runtime. Team A followed the simplest process with just three states: an initial group discussion at the regular table, followed by the continued design of the two candidate designs at the interactive tabletop, completing one before starting the second (see top-left state diagram in Figure 6). Similarly, Team B followed a similar design process with the addition of a meta-analysis comparing the two candidate designs displayed on different devices (one at the tabletop and the second at the IWB) and using the visualisations shown in the dashboard. Another difference is that in this group only one member actually built the designs using the tabletop, while the other two participated in the verbal interaction, working as advisors (Figure 6, top-right).

The design process followed by Team C included an explicit sub-process during which members negotiated their individual agendas by writing their agreed objectives on the writeable wall. Thereafter, they divided the work so one member worked at the IWB while the other two worked at the interactive tabletop to generate two similar candidate designs. During this time they used the projection for information retrieval about the course, as well as the paper-based materials. Then they merged the work so the three participants completed one of the designs at the tabletop, occasionally updating the second design using the IWB (Figure 6, bottom-left). Finally, the design process followed by Team D was more complex and less linear than the other teams. Team members negotiated their objectives by writing them on the writeable wall, and built the designs using both the IWB and the interactive tabletop, often in parallel but also iteratively, also using both large devices to examine the designs. Members were aware of what each other was doing, and kept their list of objectives and the designs updated simultaneously. They also used the paper-based materials for information retrieval. They completed the task with a meta-analysis of both candidate designs and by checking that they addressed their agreed objectives (Figure 6, bottom-right).

Analysis 3 – Roles and divisions of labour
Q3: What strategies were followed by each group in terms of their social roles and divisions of labour?

This analysis was grounded on the CSCW view of roles as human constructs created and sustained during the interactive activity [44]. Thus, to understand how the roles proposed to users were enacted (and co-configured), and inspired by previous work aimed at automatically detecting the emergence of leadership and divisions of labour (e.g. [48]), we conducted a video-analysis of the sessions that included a search of: 1) the degree of differentiation in behaviour, depending on each member’s role (e.g. whether the suggested roles were enacted by the participants during the activity); 2) the presence of strong leaders; 3) divisions of labour and responsibilities (e.g. whether participants worked altogether or divided some tasks); and 4) the monitoring ratio, measured as the division of time between attention and task-work using the shared devices (IWB, tabletop, dashboard, projection and wall). In this section we present the key findings for each team.

Team A was characterised by a low differentiation of roles. All team members spent more time performing task-work using the CoCoDes than monitoring the task (ratios between attention and task-work were 1:3, 1:6 and 1:2 for the three team members). The Quality Assurance Officer (QAOA) and the Learning Designer (LD) used the tablets...
and paper-based materials while working on the tabletop. They worked sxs without splitting the work during the design task (e.g. Figure 7, top-left). Members of Team B, like Team A, did not move from the same physical disposition around the tabletop. They worked f2f and sxs as in Figure 7, top-right. However, members of this team assumed their roles very strictly. The Lecturer (Lc) built the two designs while the LDc (holding a tablet in Figure 6) and the QAOc, acted in advisory roles and did not touch the tabletop. The LDc justified this in the interviews by indicating that they left the Lc to do most of the work to let him take ownership of the designs they were building. The team members assumed the allocated roles as if they were in an authentic collaborative design situation.

By contrast, members of Team C split the task during part of the session (Figure 7, bottom-left). Members of this team used the writeable wall to externalise their agreed joint goals. The Lecturer (Lb) was a strong leader and spent most of the time coordinating and guiding the other members towards his allocated goals (the attention to task-work ratio of the Lb was 4:1 whilst other members were 1:1 for both the LD and the QAOb). Finally, for Team D the workload was distributed among all the roles. Team members moved quite frequently in the space, using the writeable wall to keep track of all the changes in the design being constructed in both the IWB (e.g. Figure 7, bottom-right) and the interactive tabletop. The QAOd focused on monitoring the accomplishment of the team’s objectives while the other team members spent less time monitoring the displays and more time building the designs (attention to task-work ratio was 1:1 for QAOd whilst 1:2 and 1:3 for the Ld and Ldo respectively).

**Discussion: the Framework Applied across Analyses**

This section describes how the integration of the analysis methods, aligned to the four components of group activity, can explain each team’s activity in our design studio and, where possible, make meaningful comparisons between teams.

Table 2 presents a brief overview of the analyses described above. Team A constrained itself to only working sxs at the tabletop, without moving around in the space, with members holding tablets or paper materials and using the projected PC to guide and monitor their activity (set component). The design intention was that they would use the writeable wall to write up their negotiated goals and compare their final designs, however, they did not. Team A adopted the simplest linear process of all the groups to build the two candidate designs requested (epistemic). Interpreting this in line with the ACAD framework, we can say that Team A re-configured the task at runtime according to their understanding. Team A also did not differentiate roles in the group (social) and the three users felt frustrated at not achieving their individual goals, struggling with user interface aspects.

In Team B, in contrast, the roles strongly shaped the interaction. Team members also worked only at the tabletop, but adopting a f2f formation. The team made a runtime decision to assign the role of ‘doer’ to one member, and ‘advisors’ to the other two (social). These roles influenced the way in which members used the tools available. The advisors were looking at the tablets, papers, the other vertical screens, and the dashboard, while the doer interacted with the tabletop (set). Team B also adopted a linear process in completing the task, with an additional phase of analysis of their two designs (epistemic). As with Team A, the simplicity with which these teams approached the task shaped the way they used the space and the tools available (epistemic shaping the tools usage). Team B followed the intended design more systematically with respect to the roles. However, they did not follow other aspects suggested as part of the task (for example, the suggested negotiation of individual goals - epistemic). The similarities and differences in the activity of the users in the two groups was observable in the similar linear process but different physical formation and tools usage.

Teams C and D also had commonalities. They both used the tools and space more extensively, including the writeable wall to externalise and negotiate their individual goals and then to monitor the design activity. In both teams, users did not keep the same formations in the space, using both the IWB and the tabletop to design and visualise the two candidate designs (set). The process adopted by Team C was both linear and parallel at times (epistemic). In Team C, a strong leader coordinated the task approach (social). Influenced by the loose enactment of roles and the presence of a leader, the team showed different formations, sxs and f2f, and diversity in the tools used, and changes in the workflow (social component shaping the tools use and the task). By contrast, the distribution of the workload was more even in Team D, with some noticeable differentiation of the roles of each member (social). The roles also

<table>
<thead>
<tr>
<th>Analyses</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>User experience</td>
<td>1 frustrated 3 inefficiency</td>
<td>1 frustrated 3 inefficiency</td>
<td>No issues reported</td>
<td>1 frustrated 2 inefficiency</td>
</tr>
<tr>
<td>Tools use</td>
<td>Tablettop</td>
<td>Tablettop (1 member only)</td>
<td>Tablettop, IWB and Wall</td>
<td>Tablettop, IWB, dashboard and Wall</td>
</tr>
<tr>
<td>Attention</td>
<td>Projector</td>
<td>Dashboard, IWB, Projector</td>
<td>IWB, Wall</td>
<td>Dashboard, Projector, IWB, Wall</td>
</tr>
<tr>
<td>Space and mobility</td>
<td>Fixed: Set at the tabletop</td>
<td>Fixed: 1 f2f and 2 sxs at the tabletop</td>
<td>Variable: 1 at IWB, I2f/sxs at the tabletop, sxs at the Wall</td>
<td>Variable: sxs at all the large devices</td>
</tr>
<tr>
<td>Process</td>
<td>Linear work</td>
<td>Linear work + meta-analysis</td>
<td>Parallel and Linear work</td>
<td>Parallel, iterative work + meta-analysis</td>
</tr>
<tr>
<td>Roles</td>
<td>Low differentiation</td>
<td>Strict enactment</td>
<td>Loose enactment Strong Leader</td>
<td>Strict enactment, distributed workload</td>
</tr>
</tbody>
</table>

*some details are not shown (e.g. tablets and paper materials usage)
influenced the ways in which the space and tools were used by this team, adopting sxS formations at all the large devices (reflecting the similarity of their workload) and showing a more complex process with periods of parallel work. Like Team B, this group also heavily used the dashboard to support the meta-analysis of their candidate designs, as a result of the more strict differentiation of roles.

Overall, the analysis approach captured a set of elements that each contribute valuable dimensions to understanding the complexity of the group processes in this heterogeneous setting. The ACAD dimensions provide a clear overview of the different aspects that can shape the groups’ activity (as in Table 2) that go beyond the sole set design (e.g., user interface design). This is important as it can inform the further re-design and refinement of the user interfaces and the space, in light of the social and epistemic context. Alternatively, the analysis also illustrates the flexibility of this particular space, and how it enabled people to use such different strategies.

CONCLUSIONS

The design of effective multi-surface spaces requires a clear understanding of the multiple dimensions that can shape group activity. There is a need for conceptual approaches to address the critical challenge of designing effective interfaces while keeping an explicit connection with the underpinning context of usage. In this paper, we proposed an actionable approach, to provide structure to the analysis and understanding of group activity in multi-surface spaces. The approach we have developed relates theories of group activity to the ACAD framework and proposes the application of multiple methods of analysis. The approach is deliberately and explicitly pragmatic – based firmly on the knowledge needs of the people who want to understand the actual impact of the design of the system of interest. To the best of our knowledge, the ACAD approach is unique in so far as it offers ways to disentangle activity from the epistemic, physical/digital and social entities that situate it. While these situating entities are (at least in part) designable, activity itself is not. Yet activity is what matters – it is how tasks are completed.

The richness of the approach has been illustrated with a study of 4 teams doing an open and complex design task. Three example analysis questions were addressed to understand the complexity of, and the multiple factors that can affect, the runtime activity. The varied ways each team performed in the studio, even though they all were asked to enact the same task and roles, and had the same set of tools available, illustrate the multiple factors involved in groups’ activity in multi-device spaces. It can be seen that it is no easy task to get a global view of groups’ activity, nor to measure or even gain an appreciation of the complexity of the activity in the interactive space. This is beyond the capacity of a single analysis method.

In order to situate our approach in the wider literature of ethnographic approaches to group work, we should understand that ACAD provides some ways to sensitise the researcher or the designer to look at the physical, the digital, the social and the epistemic dimensions of activity and to distinguish these elements from emergent activity. Thus, it may be said that ethnography provides both a theoretical framing and a preference for observational and interview techniques, but ACAD can sensitise the ethnographer to look at relations between certain aspects of the group activity. In short, our approach can be situated with respect to ethnographic methods in two ways: it can include qualitative ethnographic research methods as part of a set of mixed methods to understand complex multi-user activity; or, alternatively, our approach can be used by an ethnographer for theoretically framing the activity analysis. (A recent example was reported by Yeoman [56]).

We acknowledge that the ACAD framework’s more comprehensive analysis of group activity in multi-surface environments may be more time consuming. But it also gives a richer picture of the collaborative activity and the use of the rich set of digital tools and devices. This can provide insights into the collaboration and inform iterative re-design of the spaces. Moreover, it is becoming increasingly feasible to automate some of the analysis and even information about social roles could be elicited, potentially with cross validation within the group.

Some aspects of the collaborative group activity can be automatically captured, for example, by automatically tracking mobility and group formations [30], or allowing the detection of leaders and followers [48]. Alternatively, sensing technology can also be used to semi-automate the analysis and reduce the effort necessary to make sense of users’ activity. Some of these tools include the use of multichannel video-based analysis tools (e.g. VACA [10] and EXCITE [31]), the digitisation and synchronisation of hand-written observations (e.g. [51]), or the use of visual representations of users’ interactions (e.g. VICPAM [34] and ViTACO [49]).

Further work is needed to explore the application of the approach in other contexts and interactive spaces to demonstrate how the tools, artefacts, roles, divisions of labour, individual practices, and approaches to the task can re-shape users’ group activity in these kinds of emerging technology-rich spaces. We believe that this work provides a valuable foundation for the research needed to understand complex collaborative interactions in multi-surface digital ecosystems.

ACKNOWLEDGMENTS

This work was funded by the Australian Research Council (Grant FL100100203). The studies were conducted under protocol 2012/2794 approved by The University of Sydney Human Research Ethics Committee. The most up to date participant consent forms can be requested by email (Peter.Goodyear@Sydney.edu.au).
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