# Understanding Collaboration Around Large-Scale Interactive Surfaces

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We present findings from an empirical study of how groups of eight users collaborate on a decision-making task around an interactive tabletop. To our knowledge, this is the first study to examine co-located collaboration in larger groups (of 8-12 users) seated around a large-scale high-resolution multi-touch horizontal display. Our findings shed light on: 1) the effect of collaboration patterns of larger groups on equity of participation; 2) the role of participants' position around the tabletop in forming collaborations; and 3) the mechanisms, which facilitate coordination and collaboration in larger group interacting around large-scale tabletops; We also contribute computational methods that leverage image processing to analyze interaction around large-scale tabletops. Finally, we discuss implications for the design of large-scale tabletop systems for supporting co-located collaboration in larger groups.[1]

CCS Concepts: • **Human-centered computing~Collaborative interaction** • **Human-centered computing~Computer supported cooperative work** • *Human-centered computing~Empirical studies in collaborative and social computing*

**KEYWORDS**

Collocated collaboration; Interactive surfaces; Multi touch

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## 1 INTRODUCTION

In his seminal paper on ubiquitous computing, Mark Weiser described a vision of interconnected devices that support activities in work and leisure [65]. Work, and particularly collaborative work, is a focus of

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Weiser's vision, and visual displays of different sizes play a prominent role in enhancing this anticipated collaboration. Specifically, Weiser discusses the use of foot-scale and yard-scale displays, which are equivalent to today's tablets and large-scale displays. In the last decade, large-scale interactive surfaces have become commercially available; they are still expensive by consumer standards, but they are becoming more affordable and their availability in work and educational settings is increasing. These are exciting developments: we now have the means to implement Weiser's vision of collaboration. We can display dynamic information on large-scale devices and allow users to manipulate the information using natural interactions such as touch and gestures. However, the availability of exciting devices is not enough to design effective collaborative environments. We also need a deep understanding of how different design characteristics of the environment will affect users' ability to collaborate.

In this paper, we investigate co-located collaborative decision making around a large-scale interactive tabletop. Our goal is to identify usage patterns and considerations important for enhancing the collaboration of larger groups (6-12 users) seated around such a device. While previous work has investigated how interactive tabletops support co-located collaboration in small groups (2-4 users) interacting with an interactive tabletop (with diagonal length of 76-203 cm), there is little research on how larger groups of 8-12 users interact around large-scale (diagonal size >280 cm) interactive tabletops.

However, co-located collaborations of larger-groups of 8-12 participants have different characteristics than smaller groups, and are therefore important to study. One difference is the exponential increase in the number of communication channels in respect to group size. For example, a group of four has 6 communication channels, while a group of eight has 28 channels [4]. This significant increase in the number of communication channels makes interpersonal communication more difficult. Studies indicate that as group size increases, less communication channels are utilized and the discussion is more likely to be dominated by few participants, and recognition of expertise is also augmented by group size [29].

Co-located discussions of larger groups are also important to study because of their prevalence in real-world decision making scenarios such as board meetings, review panels, and seminar classes. For example, the average board size of businesses is 9.2 members, and research indicates that businesses with boards of 8-10 participants tend to outperform businesses with larger boards [32].

Considering the increasing availability of interactive large-scale tabletops, we anticipate that they will be incorporated into spaces such as board rooms, meeting rooms, and small classes. Thus, it is important to study how large-scale interactive tabletops could support and enhance collaborative decision making in larger groups. However, the use of large-scale interactive tabletops presents challenges that go beyond the design and usability issues of smaller interactive tabletops: the large distance between users and the longer communication channels between them reduce the information flow, and thus might require more complex coordination and communication than in smaller groups interacting with smaller interactive surfaces; the visibility of both information artifacts and of user actions is limited across the large surface; and the size of the tabletop makes different areas completely unreachable for users [47]. However, to date, there is a lack of knowledge of how these challenges impact co-located collaboration and decision making in larger groups.

In this paper, we take a first step towards this goal—presenting findings from a study of how groups of 8 users collaborate around a high-resolution large-scale interactive tabletop (diagonal length of 300 cm) while engaged in a decision-making task (Fig. 1). We decided to study *seated* interaction as it mirrors existing settings of collaborative decision making in meeting and seminar rooms, where larger groups are often seated around a table for the duration of a meeting.

The main contributions of this paper are: 1) expanding the body of knowledge on co-located collaboration around interactive tabletops by shedding light on the mechanisms that support collaboration and coordination in larger groups seated around a large-scale tabletop and their effect on equity of participation; 2) introducing novel computational methods that leverage image processing for analyzing interaction on and around large-scale tabletops; and 3) deriving implications for the design of large-scale tabletop systems for supporting co-located collaboration in larger groups.

# 2 RELATED WORK

## 2.1 Interactive Surfaces

Large vertical interactive surfaces are increasingly available in collaborative settings and have been studied extensively. The first fully-developed digital whiteboard system, LiveBoard [12], was followed by several commercially available and research prototype systems. Despite their demonstrated success in facilitating information sharing [22, 31], interactive walls afford only side-by-side, rather than face-to-face, interaction and are thus are less compelling for extended collaboration and discussion than tabletops [49].

Many tabletop systems have been developed in both research and industry, e.g. [11, 18, 20], establishing benefits in augmenting group meetings and supporting co-located collaboration for small groups (2-4 users). In addition, research has explored small group collaboration around a tabletop [19, 33, 37, 48, 51, 52, 57, 62, 63] and the effects of varied interactive tabletop parameters on co-located collaboration, e.g. [5, 6, 9, 24, 25, 28, 38-40, 46]. However, most tabletop systems studied in this body of work have a diagonal size of 76-203 cm and support small groups, while the study we present in this paper employs a tabletop display with diagonal length of 300 cm, designed to support seated interaction in larger groups of 6 -12 users.

Multi-device environments—which integrate large wall displays, and a multi-touch table, such as iRoom [23] and WeSpace [66]—offer additional benefits for information visualization and co-located collaboration. Still, the interaction is often limited to small groups (of 2 - 4 participants) due to the size of the tabletop.

Early work informing the study of interactive tabletops investigated the use of non-augmented tabletop workspaces, demonstrating that tabletops provide a relatively high degree of workspace awareness, through peripheral awareness of both table artifacts and user actions [61]. Research has identified orientation and partitioning as crucial mechanisms for mediation of group interactions [26, 61]. The position of collaborators around the tabletop was found to be important in establishing partitions between collaborators, with the area closest to each user identified as personal space [26]. Scott et al. [53] found that partitioning is part of the more complex practice of establishing territories within a tabletop workspace. They observed the use of three (not necessarily mutually exclusive) types of interaction areas —personal, group, and storage—between which the boundaries were quite flexible. Once again, the tabletops used in these studies were small (a diagonal size of less than 200 cm) and involved groups of 2-4 collaborators.

## 2.2 Design Considerations for Tabletop Interactions in Large Groups

Several researchers have reflected on design considerations and guidelines for tabletop interaction. Shen et al. [59] detailed usability challenges for designing tabletop applications including: content orientation, occlusion and reach, interaction with distant or obscured information artifacts, gestural interaction, and Walk-up and walk-away usage issues. Carpendale et al. [7] proposed interface metaphors and components for tabletop displays to address the problem of orientation and provide users the freedom to organize and annotate content in a flexible manner. Wallace and Scott [64] identified five contextual factors for interactive tabletop design: social and cultural, activity, temporal, ecological, and motivational. These factors are further discussed in relation to three main aspects of a tabletop system: software interface, physical form, and connectedness. This work also focuses on tabletop systems designed to support small groups of 2-4 users.

To investigate the effect of group and tabletop size on collaboration, Ryall at al. [50] studied groups of two, three, and four users on a collaborative task around an interactive tabletop measuring either 80 cm or 107 cm, diagonally. They found that speed of task completion was affected by group size but not tabletop size, and observed that the size of the group affected how shared resources were managed, and how resource distribution affected work strategies. In groups of two, users worked more collaboratively, while groups of three and four worked in parallel with a single user managing the shared resource, shifting to a collective work strategy nearing completion of the task. Mahyar et al. [33] evaluated a tabletop-centered multi-display environment consisting of a large multi-touch surface, an interactive wall, and personal devices for engaging the public in collaborative urban design with groups of 4-5 participants standing and interacting with the environment.

Previous work has also highlighted the importance of coordination mechanisms for group success. Tang et al. [60] investigated collaborative coupling and the transitions between coupling styles in pairs. Morris et al. [41] observed that social protocols are not always sufficient coordination mechanisms for collaborative co-located group work around an interactive tabletop and proposed a series of coordination policies. The awareness evaluation model, developed by Neale et al. [44] frames work coupling in five levels from loosely to tightly coupled, dependent on the communication demands of the activity at hand.

Shaer et al. [58] observed how groups of 6-17 participants used a (non-augmented) conference-table space in data-driven meetings. They noted that: (a) the use of personal information devices such as laptops and tablets is ubiquitous in meetings; (b) physical artifacts are often included in meetings; (c) participants that are sitting away from the table are often less engaged; (d) participants often sit next to other participants with whom they work closely and share information on a regular basis with; (e) throughout a meeting participants were switching between four main work patterns: 1) working individually, 2) working in sub groups, 3) discussing as a whole group, and 4) presenting to the group using a shared display. Often, transitions between work patterns would have apparent seams. They also describe usability challenges of large-scale interactive tabletops, identifying issues that go beyond those presented by interaction on smaller tabletop interfaces including out-of-reach areas, complex coordination and communication, limited visibility, and the need to support various work patterns. However, they did not conduct an empirical study of how groups of users collaborate around large-scale augmented tabletops. Here, we extend this work by presenting findings from such empirical investigation.

## 3 USER STUDY

We conducted a study to investigate how groups of eight participants work together while seated around a large-scale high-resolution multi-touch tabletop display.

### 3.1 Task

We examined a decision-making task where student participants are asked to work in groups to make funding decisions for projects aimed at improving their College. Participants were asked to collaboratively review 135 funding opportunities organized by four categories and select by consensus a subset of five projects to be funded. They were instructed to include choices from at least three different categories, and to verify that a diversity of students and academic departments benefit from the funding.

In this task, participants make collaborative decisions, resulting in a portfolio of candidates selected from a larger pool, which satisfy selection requirements. We chose this task for its similarity to important real-world problems such as selecting conference papers, making funding decisions for research or investment portfolios, and accepting students to academic programs. In addition, the task facilitates mixed-focus collaboration, where group members transition frequently between individual and shared activities [14], and thus allows us to examine whether and how a large-scale interactive tabletop supports various working styles.

### 3.2 Interface

To support this task, we developed an interface based on the MultiTaction Experience application [43], which is designed to present different types of media in a highly interactive multi-user setting. We customized the interface using the MultiTaction Cornerstone SDK. We chose the MultiTaction Experience application as a basis for our interface since it has been used by many users in various contexts (e.g. show rooms, museums, conferences) and has not been designed for supporting a particular working style.

In our study, the interface presented users, upon touch, with a higher-level menu, which contains four categories of projects to fund. Users could browse a hierarchal tree menu organized by funding categories until they found project cards of interest (see Fig. 1). Once a project card is open, it is persistent and stays on the tabletop until removed by a user. However, idle open menus fade after 10 seconds.

Multiple copies of the same project card could be open on the table. Users can scale, move, and reorient cards through standard multi-touch gestures, as well as annotate cards using an infrared (IR) pen. When a user annotates and closes a card, the annotation is saved and will appear on all copies. Users can also write and draw anywhere on the tabletop.

## 3.3 Apparatus and Setting

We used a large-scale multi-touch tabletop (121.4 cm by 274.3 cm) (Fig. 1), which consist of four 55'' Ultra-Thin Bezel MultiTaction cells with a resolution of about 40 pixels per inch. The display supports unlimited simultaneous touch points using an IR light and camera system, and enables annotation using IR pens. The screens are embedded in a tabletop frame with a height of 79 cm from the floor and a bezel of 28 cm so that the table supports comfortable sitting with sufficient space for personal devices on the bezel.

Participants were seated in eight standard height-adjustable office chairs around the table. The area of the interactive space was 33,300 $cm^2$ in total (4162.5 $cm^2$ per user). At the beginning of each session, all chairs were adjusted to the same height and placed within the same positions around the table. However, during the session, participants could adjust their chairs and move them as they saw fit. Due to the limited availability of the IR pens in our research facility, each group of participants was handed three IR pens to share, which were placed in the same positions at the beginning of each session.

To analyze on-table and off-table activity, we used a wide-angle camera (GoPro HERO) mounted above the tabletop. The camera covered the entire tabletop (see Fig. 1), and captured 1920×1080 pixels at 30 frames per second. In addition, to facilitate video coding of physical and verbal participation, we used two video cameras (Sony CX560) placed in fixed positions using a tripod (see Fig. 1), so that each captured four participants.

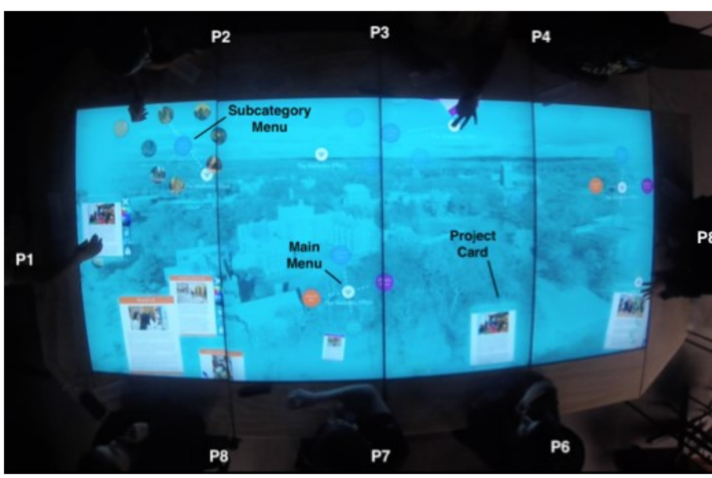


**Fig. 1. Still image from overhead camera of session D during the task (3:03), annotated with the starting positions of each participant and labels for table artifacts. Eye-level cameras were positioned at the top left and bottom right.**

## 3.4 Participants

We recruited 40 undergraduate students by email (38 female, one gender non-conforming, one male; age M=20.0 SD=1.09) to participate in the study in groups of eight (5 groups). Participants received a $10 gift card. Participants knew each other as students (14), friends (8), coworkers (7), teammates (2), or roommates (2). Similar levels of acquaintance are typical in ad-hoc student committees, where student representatives meet to make decisions about various aspects of student life.

Several studies indicate that gender composition affects group dynamics in co-located discussion e.g. [3, 27, 45, 67]; Wooley et al. [67] found that a general collective intelligence factor for group performance was positively correlated with the number of females in a group, an effect possibly moderated by social sensitivity. Aries [1] found that all-female groups tended to have a “rotating” conversation style, while most women were interrupted or under-participated when interacting in mixed-gender groups. For this reason, our current study focuses on (almost) all-female groups, where conversation style could potentially benefit from using a shared interactive tabletop.

## 3.5 Procedure

Participants were briefed and signed a consent form. In groups of four, participants completed a 3.5-minute tutorial on the tabletop interface. While waiting, the other four participants sat out of view of the tabletop display. After all participants completed the tutorial, the chairs around the tabletop were reset into the positions depicted in Fig. 1 and all eight participants were instructed to seat themselves (no assigned seats). The researcher instructed participants to choose five funding opportunities from at least three subcategories that would benefit a diverse group of students and academic departments. Participants were told to come to a consensus as a group through discussion and not voting, and that there was no time limit for the collaborative task. No other instruction was given about how the participants should work on the task. The researcher then passed out printed copies of the task instructions to all participants and instructed the participants to begin working on the task.

During the task, the researcher did not interact with the participants. After reaching a consensus, participants called the researcher over and presented their group choices and rationale. Participants were asked to fill out an anonymous online post-task questionnaire, taking turns on four laptops provided by the researcher. On average, the entire session lasted 55:54 minutes (SD = 02:36 minutes).

## 3.6 Data Collection and Analysis

Several types of data were collected and analyzed. First, video was recorded from three angles for each session: two eye-level cameras and an overhead camera. The two eye-level cameras also recorded audio. All three cameras were clearly visible and pointed out to the participants before the study, but were not obtrusive to the task. The recordings comprised just under 3 ½ hours total, excluding time spent on instructions and questionnaires. On average, groups spent 29:10 minutes on the collaborative task (SD=3:27 minutes). These recordings were video coded using ATLAS.ti. Video footage from the overhead camera was also used for automatically calculating the activity on and off the table throughout the session. Each group's final selections were evaluated based on the information artifacts (project cards and notes) they presented to the researcher during the presentation phase. Finally, we collected answers to the questionnaire.

### *3.6.1 Manual video coding.*

For describing participants' collaboration, we coded the verbal communication, physical interaction, and working style of each participant. Physical interaction was coded from the overhead camera, and verbal communication and working style were coded from one of the two eye-level cameras: camera 1 for P5-P8 and camera 2 for P1-P4. These codes were developed based on relevant literature (e.g. [21, 22, 57]) and through iteration on pilot data. For each user in each session, we coded:

*Verbal communication.* We annotated the segments of the session video in which the specified user spoke. The content of each segment was coded as *on-task* or *off-task*. On-task verbal communication was further classified as supportive (in favor of a suggestion by another user) or unsupportive (opposed to a suggestion by another user), or neither. Additionally, we annotated utterances regarding spatial strategy (e.g. "Let's put the ones we like in the middle") and work-division strategy (e.g. "We'll look at Sense of Place and you two should look at 21st Century Impact").

*Physical interaction.* We annotated the segments of the session video in which the specified user was interacting with the surface. Interactions with the surface were categorized into collaborative and non-collaborative actions. Collaborative actions include: passing an artifact to another user; adjusting the size or orientation of an artifact to share with others; and writing a note for group reference. Non-collaborative actions include: adjusting an artifact for self; writing a note for self; and all other touch interactions. In Table 3, we also highlight cases in which *off-table* physical interactions served as coordination mechanisms.

*Working styles.* We divided the session video into mutually exclusive segments based on the working style of the specified user: parallel (working independently), pair/small group or group, and off-task. Pair/small group collaborations were further annotated as open (inclusive of other users) or closed (exclusive of other participants).

From this annotated video data, we tallied the instances and durations of each code for each participant throughout the session. This data was further aggregated across each session and is presented in this paper on both the individual and group levels (see Table 1).

The 3 ½ hours of recordings were coded in three separate passes. In the first pass verbal communication was coded as described; the second pass focused on physical interactions; and in the third pass, working styles were coded. Three researchers inter-coded with 30% overlap, which totaled (after three passes) 10 hours, 30 minutes of analyzed video. All three researchers discussed and refined the coding scheme. We calculated time-unit Kappa with tolerance as $\kappa$ = .82 for verbal communication, physical interaction, and working style [2], using a 2-second tolerance as recommended by Mudford et al. [42]. Average coder agreement was 94% for verbal communication, 92% for physical interaction, and 90% for working style.

#### *3.6.2 Automated video processing.*

We developed an automated process to analyze the videos recorded from the camera mounted above the tabletop. The process applied image-processing methods to analyze frame-by-frame changes on- and off- the tabletop. More specifically we applied the following methods:

*Heatmap.* We created a heatmap of movements on and around the table for each group, which graphically represent user activity on and around the table (Fig. 2). We calculated pixel-wise differences between individual video frames, and counted such changes for each pixel for the entire video. A difference in a pixel between two frames means either that a participant moved or that an element of the display changed. We represented the number of changes for a pixel with a spectrum of colors, where blue indicates few changes and red indicates many changes.

*Activity timeline.* We measured the activity on- and off- the table, in changed pixels using the values the heatmaps produce (Fig. 5). The sum of the changed pixels on a frame indicates how active or passive people are behaving while working together. The value for the activity outside of the table contains information about any kind of movement the participants make, such as leaning in or moving closer to another participant, or adjusting their chairs.

*Percentage of area covered on the table.* For each frame, we compared the image to an image of an empty table. This gave us information of whether information artifacts (e.g. notes or cards) are present on the table in the current frame, providing us with additional insight into how a group works with the surface and how much they use it during their collaboration.

#### *3.6.3 Post task questionnaire.*

Our questionnaire inquired about participants' experiences. In particular, we measured: subjective *satisfaction* from collaboration using a slightly modified version of the Decision Scheme Satisfaction subscale from Green and Taber's questionnaire on group process [13]. We also inquired about participant use of *personal space* and *enjoyment*. For the personal space measure, we used the following three questions: "I had sufficient space on the tabletop to work on this scenario.", "I was concerned about spilling into other people's space on the tabletop.", and "I was concerned about other people spilling into my space on the tabletop." For enjoyment, we employed Davis et al's perceived enjoyment scale [10] without modifications. All questions used a 5-point Likert scale.

## 4 RESULTS

### 4.1 Performance and Participation

All five groups completed their task successfully; selecting five projects to fund collaboratively while satisfying the requirements specified in the task instructions. For each session, we recorded the time from start until the researcher was called over for presentation (M=0:26:15, SD=0:07:17), and the duration of the presentation to the researcher (M=0:02:55, SD=0:01:06). Combined, these two durations result in total time on task (M=0:29:10, SD=0:06:27).

We recorded verbal and physical participation per participant based on the coding scheme discussed above. For each session, we calculated the average duration of verbal participation and of on-surface interaction per participant (see Table 1). These durations are the averaged total amount of verbal participation (any speech) and on-surface interaction (any surface touch) for each user. We also noted the dominant collaboration pattern per group in terms of duration (see Table 1).

**Table 1. Performance results per session in terms of time and participation, and equity of participation [17]**

| Group | Collaboration pattern | Time until / duration of presentation | Verbal participation per user (MM:SS) | Equity of verbal participation (time) | On-surface interaction per user (MM:SS) | Equity of on-surface interaction (time) |
|---|---|---|---|---|---|---|
| A | All group | 33:27 / 2:46 | 5:20 (2:48) | 0.278 | 13:27 (7:04) | 0.277 |
| B | Group of 4, two pairs | 32:15 / 1:44 | 6:11 (3:07) | 0.262 | 11:19 (3:51) | 0.167 |
| C | All group | 19:42 / 2:57 | 3:31 (2:30) | 0.376 | 7:14 (3:03) | 0.223 |
| D | Four pairs | 17:30 / 4:42 | 3:11 (1:20) | 0.222 | 4:27 (1:50) | 0.217 |
| E | Four pairs | 28:23 / 2:24 | 5:54 (2:28) | 0.194 | 7:18 (3:16) | 0.226 |

## 4.2 Equity of Participation

Groups with a dominant global collaboration pattern (a single group), exhibited less equity of participation. The highest equity of participation was in groups where the dominant collaboration pattern was four pairs. This result is consistent for both verbal and physical participation. Equity of verbal and physical participation is visualized in Fig. 3.

We calculated equity of participation using Gini coefficient which produces a value between 0 and 1, the closer the value to 0, the higher the equity [17]. We computed two separate Gini coefficients measures for each session: for total time of verbal participation per user and for total time of on-surface physical participation per user. In terms of verbal participation, groups D and E, where participants worked in four pairs, had the lowest Gini coefficient (most equity), and the highest Gini coefficient (least equity) was found in group C where the dominant work style was a single group discussion. This group also included the only male participant (C5), who chose a seat at the head of the table and moderated much of the conversation.

In terms of physical participation, Group B where participants worked in small groups of four and two pairs had the lowest Gini coefficient (most equity) and the highest Gini coefficient (least equity) was in group A where participants worked as a single group. Table 1 shows these results.

## 4.3 Interaction Space

Participants perceived space as limited and were moderately concerned about others intruding to their space and about spilling into others' space (see Table 2). We observed that participants used the space in front of them, attempting to use any space they can while adhering to social conventions.

Boundaries of personal territories were not static. For example, in session E, participants broke into four pairs with each pair occupying roughly a single tiled screen (from various orientations). During the local collaboration phase, users E6 and E7 interacted at the center of the screen, possibly because there were no participants directly across from them whose space they would be invading. These updated boundaries remained consistent through the internal presentation phase.

The area at the center of the tabletop was primarily used as a group space. In groups A and C, where the dominant working style was global collaboration, participants pooled project cards in the center for at least part of the session. In groups E and A, where the dominant working style was local collaborations, the middle of the tabletop was used during the internal presentation. Fig. 2 shows heatmaps for on- and off-tabletop activity.

**Table 2. Workflow, Decision Scheme Satisfaction [13], Perceived Enjoyment [10], and three personal space measures on a five point likert scale (1-strongly disagree to 5-strongly agree)**

| Group | Collaboration pattern | Decision Scheme Satisfaction α = .752 | Perceived Enjoyment α = .857 | *sufficient space to work* | *concerned about spilling into other people's space* | *concerned about other people spilling into my space* |
|---|---|---|---|---|---|---|
| A | All group | 4.00 (0.64) | 3.50 (1.27) | 3.00 (1.15) | 4.28 (1.25) | 2.71 (1.11) |
| B | Group of 4, two pairs | 4.22 (0.52) | 3.66 (0.96) | 2.25 (1.03) | 3.88 (1.12) | 3.75 (0.88) |
| C | All group | 4.56 (0.32) | 4.16 (0.39) | 3.88 (0.99) | 3.62 (1.50) | 3.25 (0.88) |
| D | Four pairs | 4.82 (0.47) | 4.01 (0.84) | 2.86 (1.21) | 3.43 (1.39) | 4.00 (0.81) |
| E | Four pairs | 4.91 (0.12) | 4.13 (0.59) | 3.25 (1.28) | 3.13 (1.24) | 3.50 (0.92) |

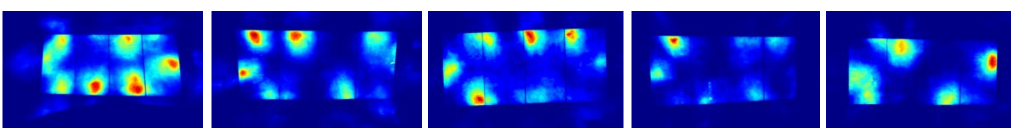

**Fig. 2. Heatmaps of on- and off-table activity, aggregated across the session from the overhead camera, for G1-G5 from left to right. Red areas indicate more activity, while dark blue areas indicate little or no activity.**

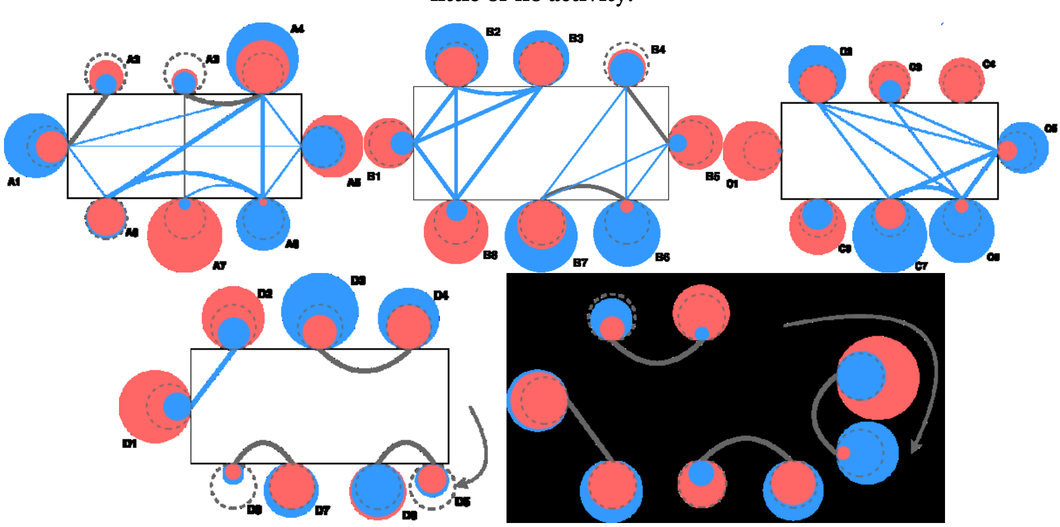

**Fig. 3. Visualization of participation and collaboration patterns per group. Each circle represents one user's percentage of participation in their session—verbal participation in blue, on-surface interaction in red, and a dotted gray circle representing perfect equity of participation. Lines denote interaction between participants—verbal collaboration in blue, verbal and physical collaboration in gray—with thicker lines denoting more frequent interaction. Seat movement is denoted by arrows.**

#### *4.3.1 Moving seats.*

We observed two instances of participants moving locations for planned local collaboration (Fig. 3). In both cases, users moved from their original position to a new location with a better shared orientation.

#### *4.3.2 Bezel.*

The bezel around the interactive tabletop played an important role facilitating non-verbal cues such as leaning in while engaged in the task, leaning back while disengaged or when completing a sub-task, and shifting weight to indicate attention to a particular speaker (Fig. 4). All participants placed their task instructions on the bezel directly in front of them, and some placed their personal devices in this area.

**Fig. 4. Participants A1 and A2 lean on the bezel while collaborating locally (left) and away from each other during global collaboration (center). Participant A4 (right) disengages from the bezel between the final group decision and presentation.**

## 4.4 Task Workflow

All groups started working on their task by engaging in parallel work with an occasional open discussion of the interface. Then, groups moved into strategizing about the task. At this stage, groups B, D, and E decided to split into smaller groups for local collaboration (based on proximity) as a result of a mutually agreed upon strategy suggested by one or multiple users. B split into two groups of four, one of which further split into two pairs, while D and E immediately broke into four pairs. In groups B and D, one user assigned domain subcategories to the small groups, while in E, E8 asked each pair which subcategory they wanted to explore and assigned the last remaining category to herself and E7.

Some of these local collaborations included physical collaboration, and all included closed verbal collaboration between local group members where the only verbal exchanges between different local groups was monitoring regarding the interface and moderation instigated by a single user asking the larger group if they were ready to reconvene. These local collaborations were all followed by a period of internal presentation where members of each local group presented their choices to the larger group, followed by full group discussion until they reached consensus. Thus, groups that broke into smaller local collaborations reached consensus in two stages--within their local collaboration and then again during the internal presentation phase.

Alternatively, groups A and C did not break into planned local groups, instead they both held a continuous open global discussion. Group members transitioned fluidly between parallel work, brief open local collaboration, and global group discussion. Potential projects were presented and each was discussed individually until the group has reached consensus about whether to include it in their final five selections. These groups reached their final consensus after proposing and agreeing on a fifth selection.

At this stage, per the task instructions, all groups called over the researcher and presented their choices. Presentation style varied between groups, but not as a function of task workflow. Group A and Group B did not display project cards on the screen and instead one user presented from paper notes and memory, and other users jumped in. Group C oriented their choices toward the researcher and the presentation was moderated by C7, presenting one opportunity and then asking others to present each subsequent choice. Group D oriented their choices toward themselves and each pair presented the choices they found. Orientation in group E is consistent with the orientation of the background. They presented pair by pair with slight nonverbal moderation.

## 4.5 Collaboration Patterns

Throughout the session participants switched fluidly between three high-level collaboration patterns: working in parallel, collaborating in small groups (local), and collaboration with the entire group (global). Proximity played a critical role in forming *local collaborations* in smaller groups. Participants formed local collaborations with users sitting directly on their left and right, but not with users across the table. Furthermore, the only participants to physically move seats during the study were members of a pair collaborating over the corner of the table—e.g. one participant seated on the side of the table and another seated next to them, on the end. In these instances, one participant moved to the immediate left or right of their collaborator, creating a shared orientation on the tabletop.

For each group, we created an activity timeline diagram such as the one in Fig. 5, summarizing on- and off- table activity and collaboration patterns. This allows us to further identify variation between groups. In the following we describe variations in collaboration patterns.

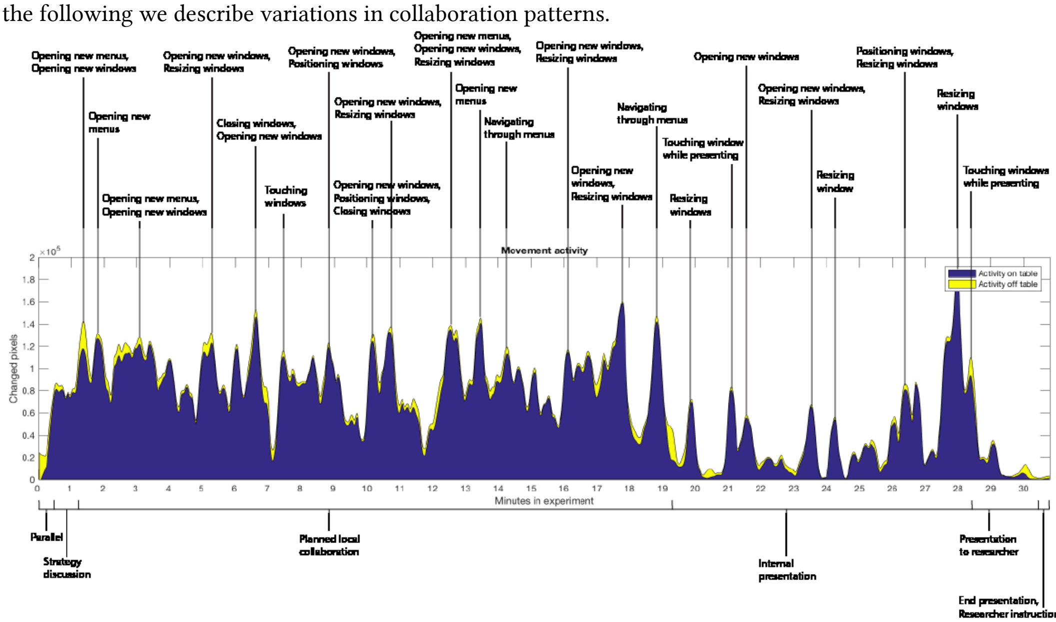


**Fig. 5. Diagram for on- and off- table activity (in terms of number of changed pixels over time) for Session E. Major peaks in activity are annotated above the timeline and changes in workflow have been marked below the x-axis.**

While *working in parallel*, participants did not contribute to group conversation, and did not physically collaborate except negotiating for table space with adjacent users. However, participants were engaged in the task, exploring potential funding opportunities.

We observed that local collaborations could form spontaneously, with explicit consent from adjacent participants; or through planning, where adjacent participants are assigned to work together. In *tightly coupled local collaborations* both participants contributed through physical and verbal interactions while working off the same menu and discussing funding opportunities. In *loosely coupled local collaborations*, participants worked off different menus while actively conversing and verbally shadowing actions. Some groups transition fluidly between loosely coupled local collaboration (discussing funding opportunities) and parallel work (searching for funding opportunities).

**Table 3. Verbal and physical mechanics of collaboration per work style**

| Style | Category | Mechanics | Examples |
|---|---|---|---|
| Global | Verbal | Conversational - ordinary conversation about the task [37] | A6 and A8 open strategy discussion, A4 chimes with task constraints. |
| | | Verbal Shadowing - running commentary produced alongside actions, for all to overhear. [7, 37] | A7 engages with A6 when reading aloud<br>C7 speaking thoughts aloud re interface and opportunities. |
| | | Verbal monitoring - explicit coordination that can interrupt the flow of action [17] | B4, B5 complete task, then B5 interrupts the workflow of the other local collaborations ("how's everyone else doing"), |
| | | Supportive cues | A3, A5 verbally (and physically) support thoughts of A8. |
| | | Verbal presentation - read aloud or present from memory without sharing the information artifact. | B7 reads full project card aloud instead of reorienting the card or asking others to open a copy. |
| | Physical | Passing (on-table)- physical exchange of ownership of artifacts in the workspace<br>Deictic reference (off-table)- information artifacts in the workplace are referred to physically [49] | A4 "can we throw things at each other? Let's check" then passes card to center.<br>B7 gestures to an artifact on the table and refers to it as "this one" while explaining it to B6 |
| | | Feedthrough (off-table)- type of information gathering by hearing or seeing of others manipulating objects in the workspace [37] | E1 takes notes, E6 hears the sounds of pen and takes notes too. |
| | | Leaning on the bezel (off-table)– indicating engagement | A2 leans toward A1 during local collaboration (Fig. 4) |
| Local | Verbal | Consent - verbal confirmation between participants before merging personal territories. | A2 to A1 "can I look off yours"<br>A4 to A3 "let's just share" |
| | | Verbal monitoring - explicit coordination that can interrupt the flow of action [17] | A6 interrupts a local collaboration between A3 and A4 to ask which project card they're discussing |
| | Physical | Moving (off-table) - changing location for closer collaboration. | E4 moves to stand to the left of E5, later moves back to original seat |
| | | Leaning on the bezel (off-table)– indicating engagement | A2 shifts to lean toward A3 and the rest of the group during global collaboration (Fig. 4) |
| Parallel | Physical | Space negotiation (on-table)- establishing workspace by adjusting and accessing information artifacts. | C5 and C4 negotiate space nonverbally by adjusting the size of their personal information artifacts to not overlap with one another |
| | | Mirroring (on-table)- mimicking another user's actions. | A4 and A5 both open and look at the same menu without verbal coordination. |

We also noticed that local collaboration could be *open* or *closed*: in open collaboration participants speak so that they could be heard by others beyond their local group and are expecting others to join the conversation. Open local groups also share information artifacts with adjacent groups. We observed that open collaboration primarily takes place during spontaneous local collaboration. Closed collaboration was common in planned local collaborations and included only the participants assigned to work within a particular local group. Groups engaged in closed local collaborations did not communicate, or expect to communicate, with other small groups about the task.

*Global collaborations* are characterized by persistent single group conversation for most of the session, which is open to all participants. Participants contribute from time to time but are continuously keeping track of the conversation. Some participants might work independently, while keeping track of the conversation, exploring and reading about funding opportunities based on larger group conversation; other participants actively listen to group conversation while either making eye contact with other group members or peripherally interacting with the screen (opening menus but not reading). Global collaborations could be moderated or not, and often transition fluidly between these modes.

Fig. 3 shows physical and verbal communication patterns for each group. Participants are represented as circles, with the radius of the circle proportional to their overall participation: blue for verbal participation and red for on-surface interaction. Blue lines indicate verbal collaboration, while gray denotes both verbal and physical interactions.

## 4.6 Collaboration and Coordination Mechanisms

In Table 3, we describe on- and off-table collaboration and coordination mechanics, applied within each of these collaboration patterns.

While there was frequent cross table verbal collaboration in the context of global group discussion, instances of physical cross table collaborations were rare (see Fig. 3).

Due to the size of the table, the visibility of both the content being explored by and the actions of fellow users was limited, particularly across the tabletop. To compensate for this lack of visibility, participants in global collaboration used verbal shadowing [8, 33, 47] – running commentary of their actions as well as deictic references to update others on their progress. Supportive verbal cues were frequent in global collaboration, serving as confirmation that users were aware and in agreement despite lack of visibility. Feedthrough through hearing (of writing on the surface) and larger off-table gestures (e.g. leaning on and off the bezel) also helped users to track the progress of others.

Coordination mechanisms also aided in the preservation and adjustment of personal and shared territory boundaries, through nonverbal space negotiation and explicit consent regarding the merging of personal territories. Groups also used verbal monitoring, which interrupted the workflow, to monitor progress.

## 4.7 Management of Limited Resources

Managing group access to shared but limited resources is a common coordination problem in collaborative workspaces [46]. In this study, information artifacts (menus, project cards) were not limited, and became available to participants upon request (e.g. touch). However, the workspace was constrained and required negotiation, through conversation or non-verbal negotiation (see Fig. 6). Additionally, with eight participants per session, conversational space was limited. Lastly, only three IR pens were provided for writing on the screen. This required verbal and physical coordination among participants to ensure the pens were either evenly distributed or to request them from others when needed.

Two groups (D and E) spread the pens out immediately, dispersing the three pens across the table. In other groups the pens remained next to the same participants for most of the session, and thus only those participants took notes on the screen. In a few cases, participants explicitly asked others to pass them the pen. We also observed behaviors to mitigate the inequality created by the limited resources. For example, E1 offered E2 and E3 the pen that she and E8 had been using, noting they were the only pair without a pen.

**Fig. 6. A4, A5, and A6 negotiate space nonverbally by adjusting the size of their information artifacts.**

## 4.8 Individual Roles

Users assume different roles throughout the session including moderator, note taker, and individual contributor. In groups with primarily local collaboration (B, D, and E), moderation was observed during the strategy phase (for planning the local collaboration groups) and during the transition from local collaboration to internal presentation. Some pairs included a note taker, others did not. In groups with primarily global collaboration (A and C), moderation was observed throughout the session and both included multiple note takers within the same global conversation. The lower verbal equity in these groups may be related to the multiple users opting for the role of note taker, rather than individual contributor.

### *4.8.1 Moderation.*

We observed several different styles of group moderation. First, users facilitated task problem solving by proposing strategies to the group either as a suggestion in question form (e.g. "Do you want to/should we..."), a take-charge statement (e.g. "We should/need to..."), or a call to action (e.g. "Let's..."). Users also catalyzed the group conversation through open ended, leading questions about strategy (e.g. "So how do we want to do this?") or inquiries about task status to catalyze the conversation (e.g. "How many have we picked so far?"). Lastly, during the internal presentation phase, as well as during final presentation, in some sessions, one user would moderate the order of presentations using verbal or gestural cues. We did not observe a pattern between seat and moderation role.

### *4.8.2 Note taking.*

In most groups, participants took notes directly on the display for personal or group reference, rather than on a project card. These notes were oriented toward the user writing them, and could not be reoriented toward others. Thus, these notes were shared verbally. Note takers recorded project titles that had been agreed upon in either their local collaboration or in the global discussion. Mahyar et al. [34] observed that manual note-taking negatively impacted awareness among group members when note-takers lost view of the screen. Contrary to this finding, perhaps because our participants were taking notes with IR pens directly on the screen, we observed participants assuming the role of note-taker as a form of engagement during global discussion, sometimes with multiple note-takers at once. These notes served as records for agreed upon project selections, and were presented verbally to the group when prompted.

### *4.8.3 Individual contributions.*

Participants contributed to the task in various ways including making suggestions regarding projects, synthesizing the expressed views and choices of others, and supporting the opinions of others.

## 4.9 Subjective Attitude Satisfaction

In general, participants were satisfied with the collaborative process (high decision scheme satisfaction). Their perceived enjoyment was moderately high. Table 2 shows the results per group. In the words of one participant (group B): "The study was very engaging in both the technology and collaboration portions, although the space was just a bit crammed. Great application of real world problem-solving, too." Overall, four participants mentioned a lack of sufficient space in their free response. One participant in group C cited the lack of space as a mechanism for facilitating collaboration: "It really felt like there wasn't enough space to keep the bubbles open, and the more densely packed options could present difficulties in finding information. This facilitated cooperation to an extent, because at times we had to work together just to find and process information."

Participants also commented on group dynamics and equity of participation. One participant from group C (which worked as a full group) noted: "I feel like some people didn't talk, but whether that was because they agreed and didn't feel the need to say anything or if it was because they didn't feel comfortable, I don't know." In contrast, another participant, from group E (with local collaboration), commented: "I liked the idea of everybody splitting into groups of two to figure out possible options for funding. In addition to the large group dynamic, it gave people the opportunity to participate in the decision-making process in a smaller group."

## 4.10 System Feedback

Participants were given space at the end of the post-task questionnaire to offer feedback on the system. Some users expressed frustration with movement of the menus, which floated across the screen when inactive. Another user commented, "I felt that Experience was fairly easy to use, but I could tell that others were struggling." Others proposed "a more permanent note taking system, because taking notes on particular slides stays for a while but tends to take up too much space."

# 5 DISCUSSION

Our findings shed light on how larger groups of eight collaborate around a large-scale interactive tabletop.

Some of our findings apply to groups in various sizes ranging from pairs to larger groups. For example, we found that groups employ various working styles and collaboration patterns within the same session, often switching strategies to adapt to different stages of the task. Larger groups might employ different collaboration patterns in parallel. For example, within the same group we might see work in smaller group of different sizes as well as parallel work. Transitioning between working styles and collaboration patterns was also observed in previous research on smaller groups interacting around a tabletop [41].

Despite the large-scale interaction surface and the increased space allocation per user compared to previous work (our study offered 4162.5 $cm^2$ per user, while previous work of groups of four allocated smaller space, e.g. 1140 $cm^2$ per user in Ryall et al. [50] and 1373.9 $cm^2$ in Morris et al. [39]), screen real estate was a limited resource. Participants continuously negotiated space and considered the space directly in front of them as their personal space and the space in the center of the table as shared group territory. Participants also applied flexible partitioning strategies, sharing space with neighbors. Likewise, these findings corroborate with the literature on smaller groups and tabletops [21, 25, 53].

However, some of our findings are **specific to larger groups** interacting around a large-scale interactive tabletop**:**

First, our results indicate that **the dominant collaboration pattern of large groups affect equity of participation**. Collaboration patterns that involve smaller groups tend to result in more equity in terms of both verbal and physical contributions. Groups where the dominant collaboration style was a global single group conversation with eight participants exhibited the least equity of both verbal and physical participation. Previous research found less equity in distribution of resources and more parallel work within groups of three and four participants interacting around an interactive tabletop when compared to groups of two [50]. However, in our study, equity was calculated in term of participation. Since access to information artifacts (menus, project cards) was not limited, it cannot explain the reduced equity of physical participation. The limited resources (IR pens) had a secondary role in the interaction, and some groups applied strategies (e.g. passing) for mitigating the inequality of access. Our findings are consistent with the literature on groups, attributing reduced equity of participation to larger group size [4]. The larger number of participants was the major factor contributing to the difference in equity, reducing the levels of both verbal and physical participation of some participants.

Furthermore, we observed that in larger groups, **collaboration is strongly influenced by position**. Participants collaborated more with their direct neighbors, less with participants sitting across from them, and rarely with participants sitting at farther ends of the table. In two cases, we observed participants moving to an adjacent side of the table for closer collaboration with another participant. It is possible that the seated interaction afforded the participants less movement than standing interaction would, despite the wheeled chairs. Small groups engaged in closed local collaborations did not communicate, with other small groups about the task. Previous research [46] have found that participants in meetings often sit next to participants, whom they already know and with whom they work closely. Thus, the opportunities for serendipitous collaboration around the table in larger groups are limited.

Finally, we found that in order to overcome the lack of visibility of both content and actions around the large-scale tabletop, participants used verbal coordination mechanisms such as verbal shadowing, supportive cues, and verbal monitoring. Often, such verbal mechanisms interrupted the workflow. Participants also applied physical mechanisms including deictic gestures, leaning on the bezel, and changing locations. While previous research on smaller groups found that much of the physical coordination happens on the tabletop through the positioning, sharing and passing interaction resources [50], **in larger groups, physical coordination mechanisms often occur off-table using speech, gestures, posture, or movement** (see Table 3) and are hence not detected by the system. This finding, in particular has implications for the design of interactive tabletops for large groups, as it highlights the articulation work, which happens away from the table, and is hence invisible to sensing. In the next section, we discuss how tracking off-table activity could enhance interactions between members not seated in close proximity.

In addition, our study contributes **new computational methods that leverage image processing for analyzing interaction around large-scale tabletops**. Combined, the activity diagrams and heatmaps allowed for nuanced understanding of how larger groups worked together around the large-scale interactive tabletop. These computational methods could also be useful in analyzing user activity in other applications where groups interact with large displays, for example in museums or in classrooms. In a museum, we might find out which parts of the display are more likely to foster collaboration, and which parts are better suited for individual exploration. In a classroom, we might explore how peer groups, or teacher-led groups, approach problem-solving in different domains.

## 5.1 Implications for Design

Our findings show how task workflows varied among groups as participants transitioned between different collaboration and work styles. Thus, indicating a need for systems facilitating co-located collaboration of larger-groups to **support a variety of work styles** as well as a seamless transition between work styles and collaboration strategies. This recommendation is consistent with previous work on smaller groups, e.g. [21, 22]. One way to support flexible transition is to offer *persistent personal workspaces.* Recognition and tracking of individual users around the tabletop could allow for a personal space that follows the user as they approach, or move around the table. To manage the limited interaction surface and to avoid disruption, a personal space could be represented as a resizable container. The use of static personal drawers was explored in prior work [16, 57] and shows promise. In systems that support automatic registration and tracking of devices, users could also choose to use a personal device as their personal container. Simultaneously, our findings, which show how some groups planned to break into smaller groups while others established spontaneous local collaborations, indicate a need to **support both transient and persistent *group workspaces.*** Such support is important for facilitation seamless transitions to and from local collaborations. Such group space should be easily created, merged, and shared. Prior work has implemented solutions for linked common work, for example, within collaborative thinking spaces [35]. However, with larger groups interacting around a large-scale tabletop, it is important to consider how to link the work not only of individuals but also of multiple smaller groups, as well as how to facilitate seamless transitions between individual work, small groups, spontaneous local collaborations, and large group discussion. In addition, solutions for seamless transitions should also facilitate transition from and into different user roles (e.g. note taker, facilitator etc.).

One of the challenges unique to enhancing collaboration in larger groups interacting around large-scale tabletops is **facilitating synergetic interaction between members not seated in close proximity**. Our findings indicate that collaboration is strongly influenced by physical proximity. We observed that participants used off-table coordination mechanisms such as gestures for deictic reference, and posture and action mirroring to facilitate collaboration across the table. One potential approach is to track and enhance such off-table coordination mechanisms, including gestures and movement, around the table. For example, pointing to a document across the table might offer to create a local copy in a group territory, such as the center of the tabletop. Recent work [30], which explored cooperative gestures for manipulating data on wall-sized displays, could serve as a starting point for considering cooperative gestures around a large-scale tabletop.

Beyond gestures, recognizing a change in gaze and head position in order to view cross-table content might trigger a subtle size increase or rotation of information artifacts. Existing work investigated combining touch with gaze to facilitate cases in which touch input is performed away from the location of visual feedback [15, 55, 56], but such technical approaches are yet to be applied to collaborative scenarios in larger groups. Posture recognition such as a lean-in vs. lean-out posture might facilitate a subtle local transition between action and reflection modes. Recognizing mirroring postures in users (e.g. lean-in, or lean-out) may suggest a global change (e.g. from exploration to presentation mode). However, any changes in the interface must be done carefully, not to interrupt the flow of the collaborative work and to ensure that users feel in control of the interface.

Another challenge distinct to larger groups working around large-scale tabletops is the reduced visibility of both content and actions. To overcome the reduced visibility, participants in the study used various indicators such as verbal shadowing, supportive verbal cues, deictic references, and posture, to update others on their progress (see Table 3). We propose to apply a ***hybrid approach* that enhances natural indicators in a co-located environment, with interface concepts used in remote collaboration.** A similar approach was explored in [36] and [54] in the context of sense making and multi-device environments. For example, local copies of information artifacts could be enhanced with shared annotation and indication of which users left notes or currently viewing the same artifact. Another example includes the use of Radar views, as explored by [14], which can be used to enhance awareness. However, when considering such design interventions, it is important to balance support for awareness with cluttering of the interaction surface.

Finally, our findings indicate that when the dominant collaboration pattern was a single large-group, equity of participation was reduced. Design interventions could **promote equity of participation in larger groups.** In particular, providing multiple on-demand copies of interaction resources reduces inequity in physical access. Inequity of verbal and physical contributions could be mitigated by providing additional channels for discussion, such as commenting and annotation. Our findings indicate that participants indeed seek to contribute in various ways by assuming different roles. Future work should examine which design interventions are most effective for enhancing collaboration of larger groups and supporting users in contributing through various roles and channels.

## 5.2 Limitations

Both our experimental task and the interface impose certain limitations on the behaviors we could observe. Our task focused on collaborative decision-making, and is similar to real-world problems in a variety of application domains including selecting conference papers, making funding decisions for research or investment portfolios, and accepting students to academic programs. However, unlike many real-world scenarios our task was short enough to be completed within a single session without pre-work done individually before the meeting. In addition, all participants in our study had similar expertise and no roles were pre-assigned. The nature of the task, a mixed-focus decision making task, might also have impacted the collaboration style. Other tasks, such as creating new knowledge, or engaging in creative activities, might result in different group behaviors. Furthermore, the behaviors of our groups, who do not regularly collaborate, might differ from those of cohesive teams. These limitations call for future work, examining behaviors of larger groups using a variety of tasks, as well as studying the behavior of larger-groups in real-world settings such as review panels and seminar classes.

All participants learned to use our interface quickly, and the interface did not appear to impede their work. However, we did not experiment with interface design through systematic manipulation of characteristics such as artifact size or location, which may also influence participant behavior. Additionally, future research should explore how the shape of the tabletop—rectangular, square, or circular—affects collaboration and coordination in large groups.

Finally, our participants were almost all women. It is likely that at least some of the observed behaviors differ in all-male or mixed-gender groups. This limitation also calls for future work investigating the behavior of gender-balanced and all-male groups.

### 5.3 Conclusion and Future Work

We presented findings from an empirical study of how groups of eight participants collaborate while engaged in a decision-making task using a large-scale interactive tabletop. Our findings expand the body of knowledge on collaboration and seated interaction around interactive tabletops, shedding light on: 1) the impact of seating position on collaboration; 2) the effect of collaboration patterns on equity of participation; and 3) collaboration and coordination mechanisms in larger groups interacting around an interactive tabletop; We also contributed novel computational methods that leverage image processing for analyzing interaction on and around interactive tabletops, and derived implications for design of large-scale tabletop systems for supporting collaboration in larger groups.

Future work includes a comparison of all-male and mixed-gender groups, as well as expanding our computational methods to analyze visual attention. Finally, we plan to expand our study to multi-device environments focusing on understanding the visual behavior of individual and groups.

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