Permulin: Mixed-Focus Collaboration on Multi-View Tabletops

Roman Lissermann[1], Jochen Huber[2,3], Martin Schmitz[1], Jürgen Steimle[4] and Max Mühlhäuser[1]

[1] Technische Universität Darmstadt [2] MIT Media Lab
[3] Singapore University of Technology and Design [4] Max Planck Institute for Informatics
[1] {lissermann, mschmitz, max}@tk.informatik.tu-darmstadt.de, [2,3] jhuber@mit.edu, [4] jsteimle@mpi-inf.mpg.de

ABSTRACT

We contribute Permulin, an integrated set of interaction and visualization techniques for multi-view tabletops to support co-located collaboration across a wide variety of collaborative coupling styles. These techniques (1) provide support both for group work *and* for individual work, as well as for the transitions in-between, (2) contribute sharing and peeking techniques to support mutual awareness and group coordination during phases of individual work, (3) reduce interference during group work on a group view, and (4) directly integrate with conventional multi-touch input. We illustrate our techniques in a proof-of-concept implementation with the two example applications of map navigation and photo collages. Results from two user studies demonstrate that Permulin supports fluent transitions between individual and group work and exhibits unique awareness properties that allow participants to be highly aware of each other during tightly coupled collaboration, while being able to unobtrusively perform individual work during loosely coupled collaboration.

Author Keywords

Tabletop; Multi-view; Mixed-focus collaboration; Collaborative coupling styles; Multi touch; Personal input.

ACM Classification Keywords

H5.2. User interfaces: Graphical user interfaces (GUI), Input devices and strategies, Interaction styles.

INTRODUCTION

In co-located collaboration on digital tabletop systems, collaborators usually interact on one common shared view. Working on different views requires spatial partitioning of the screen into several smaller views [4]. In contrast, multi-view tabletop hardware can display two or more *different* images at the same spatial location [10, 16, 17]. This allows for rendering personalized views for different users at the same location on the very same screen.

For this reason, multi-view tabletop hardware seems highly promising to support fluid transitions between different coupling styles [26] in mixed-focus collaboration [3]. The spectrum of coupling styles ranges from *tight coupling*, when all collaborators are actively working together on the same problem, to *loose coupling*, when collaborators are independently working on separate problems. Many more *mixed coupling* styles exist in-between these two ends [4]. Different coupling styles require different visualization and interaction support.

CHI 2014, April 26–May 1, 2014, Toronto, Ontario, Canada.

http://dx.doi.org/10.1145/2556288.2557405

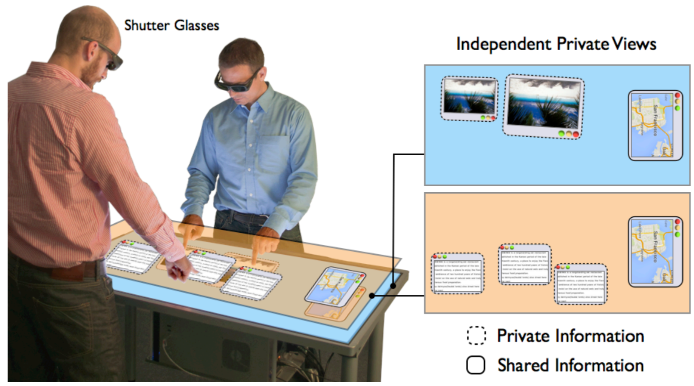

Figure 1. The multi-view tabletop provides distinct private views or a group view that is overlaid with private contents. Our techniques provide support for easy and seamless transitions along the entire spectrum between tightly coupled and loosely coupled collaboration.

Pioneering research has introduced first, promising principles for multi-view tabletop interfaces, which overlay additional private information on a shared view [1, 8, 15, 24]. Compared to classical tabletop interfaces, this provided additional personalized support during tightly coupled collaboration.

Inspired by this previous work, we aim to provide support for a considerably *fuller spectrum* of collaborative coupling styles with multi-view tabletops, covering both ends of the spectrum. Moreover, we set out to support fluent and seamless transitions between these styles.

This paper contributes Permulin, an integrated set of novel interaction and visualization techniques for multi-view tabletops. Permulin leverages on multi-view display technology to offer support for a wide spectrum of coupling styles and to support fluent and seamless transitions between them. In more detail, Permulin makes the following sub-contributions:

1. *Support of same screen group and private views:* We contribute techniques that allow collaborators to easily

and seamlessly transition between both ends of the coupling spectrum. By performing a simple grabbing gesture, the group view can be divided into two private views, which each cover the full screen. The private views provide high-resolution personal workspaces, to conduct independent work unobtrusively, as recommended by [26].

2. *Support of mutual awareness and coordination in private views:* We contribute two techniques that allow collaborators (a) to quickly share their private contents, as well as (b) to peek into their collaborator's private view. This tighter coupling supports mutual awareness and coordination while users work in their private views. The techniques provide support both for full-screen contents (e.g. maps) and free-floating elements (e.g. photos in a photo sorting application).
3. *Reducing interference in the group view:* While collaborators can effectively work in parallel on content that is juxtaposed on the shared group view, overlapping content is problematic. The resulting occlusion is disruptive and can prohibit other collaborators from accessing occluded elements. We contribute techniques that reduce such interference stemming from overlapping content in shared views. They allow collaborators to individually control the layering of shared contents. For instance, in a pile of photos, each collaborator can focus on a different photo and see the respective photo as the topmost element.
4. *Multi-touch interaction on multi-view tabletops:* All techniques directly integrate with conventional multi-touch input by providing personal input for each user. This stands in contrast to previous work on multi-view displays that did not use touch input for controlling views, but required specific head [16] or body movement [8] or tangibles [8, 15].

As a proof of concept, the techniques are implemented in a working prototype system with two example applications. This allowed us to conduct a user-centric evaluation, the first user study of collaboration on multi-view tabletops. Results from an exploratory study and from a controlled experiment show: (1) Permulin supports mixed-focus collaboration by allowing the user to transition fluidly between loose and tight collaboration. (2) Users utilize Permulin both highly cooperatively and individually. Amongst others, this is reflected by participants occupying significantly larger interaction areas on Permulin than on a tabletop system. (3) Permulin provides unique awareness properties: participants were highly aware of each other and their interactions during tightly coupled collaboration, while being able to unobtrusively perform individual work during loosely coupled collaboration.

RELATED WORK

Support of mixed-focus collaboration in close physical proximity [9, 30] has been studied using various interactive surface technologies, including single-view tabletops, secondary devices and multi-view surfaces. We discuss related approaches and our contribution in the following.

Single-View Tabletops

Group work on interactive surfaces usually requires coordination of group activities, especially in mixed-focus collaboration. Analogously to Tang et al., we define *workspace coordination* as "the management of access to and transfer of shared resources" [22, 26]. Insufficient support of workspace coordination on one interactive surface frequently results in *interference*, "the act of one person hindering, obstructing, or impeding another's view or actions on a single shared display" [31]. One example is access conflicts on a shared surface, when access to a particular interface element is disputed [18]. However, this requires collaborators to coordinate their interactions through e.g. partitioning the surface into dedicated personal and group territories [23, 27]. Although this partitioning alleviates interference, it constrains each user in both interaction and screen space. Thus, the use of single-view tabletops due to scaffolding only static *workspace awareness* [3], is likely to lead to either interference or limited space when the collaboration is loosely coupled.

Secondary Devices

One approach to overcome these limitations is secondary screens. WeSpace [28] and Caretta [25] are good examples which combine interactive surfaces for group work with personal devices for private interaction. However, these approaches require the collaborators to switch their attention between the surface and the secondary device. Furthermore, increasing the size or number of displays is not necessarily an advantage [20].

Multi-view Surfaces: Displays and Tabletops

Multi-view displays provide different views to each collaborator in the same spatial location. Some leverage on shutter technology [13, 24, 29], others on lenticular or parallax barrier displays [7, 12, 16, 19]. However, except the shutter solutions, all constrain the collaborators to a fixed position or require additional tracking systems.

These display techniques have been integrated into interactive tabletop systems, leading to *multi-view tabletops*, e.g. [1, 5, 11, 21]. Agrawala et al. [1] utilize shutter glasses to introduce layer partitioning, where different collaborators can see different layers of information on top of the group view as well as private information (additional information which is independent of the group view). These overlays allow collaborators to transition from tightly to mixed-coupled collaboration.

Overlays that depend on the collaborator's position can be implemented with optical film, which is either opaque or transparent, depending on the specific viewing angle. Lumisight [15] and UlteriorScape [6] provide distinct views for up to four collaborators, that allow for personal overlays.

Each collaborator can enable and disable these overlays with gestures or tangible objects. Similarly, PiVOT [8] enables personal overlays depending on the user's viewing angle through a combination of optical films and a display mask. As in Lumisight, tangibles can be used to enable and disable the overlays. Users have then to lean forward to be able to see the personal overlay.

While all of the above systems provide private output, they do not allow for simultaneous personal input in overlapping personal areas due to conflicting tangible objects. Moreover with respect to PiVOT, the collaborators have to lean forward to view the personal overlay. In summary, many papers have contributed *hardware solutions* for realizing multi-view displays and techniques to enable and disable the display of additional information within a group view.

We add to this body of research by contributing to CSCW research in several aspects: (1) to support fluid transitions between *coupling styles*. (2) *Workspace awareness* [3] can be dynamically adjusted in loosely- and mixed-coupled collaboration. (3) *Interference* can be reduced in mixed- and tightly-coupled collaboration. In this paper, we contribute interaction and visualization techniques for all three aspects.

PERMULIN CONCEPT AND PROTOTYPE

The central concept of Permulin (partially published in non-archival work [14]) is a tabletop interface providing (1) a group view for common ground during phases of tight collaboration, (2) private views to each collaborator to scaffold loosely coupled collaboration and (3) interaction and visualization techniques to share content in-between these views for coordination and mutual awareness. Both group and private views provide personalized multi-touch input to all collaborators, enabling them to interact simultaneously. These views are completely independent of the user's location and orientation. This is in contrast to previous work that required the user to look at the display from a specific angle to reveal private views [8, 15].

The implementation of Permulin utilizes a 52″ Philips 3D display mounted on a table frame (cf. Fig. 2). The display can alternatively switch between different full screen images due to its refresh rate of 120Hz. At the same time active shutter glasses that switch between transparency levels at high frequency are wirelessly synchronized with the display. Due to the synchronization between the display and the shutter glasses, each individual pair of shutter glasses can be mapped to an individual, unique output, resulting in each user seeing her *private* view (i.e. unique image) on the entire screen. An increasing number of such glasses (both shutter and polarization filter based) and of compatible 3D display sets are available. The screen refresh rate defines how many separate views can be offered [19]. Our current implementation offers two views. Displays with high refresh rates and corresponding glasses for more than two personal outputs have already been demonstrated [29].

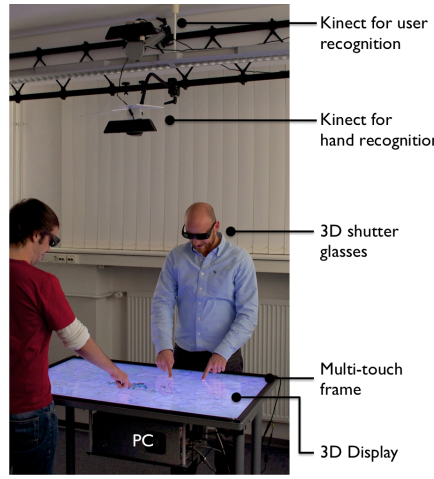

Figure 2. Prototypical implementation of Permulin

As it is the case for most screens, the display used in Permulin emits linear polarized light, matching the linear filter of the glasses. In consequence, the display would appear black when seen from its short side. We added a diffusion film on top of the screen (Kimoto 100 SXE foil), scattering the light and enabling an angle independent (360°) view on both private and group views.

User tracking and hand recognition are based on two Kinect cameras (cf. Fig. 2). The higher mounted one caters for user tracking, the lower one detects hands using a contour-based blob tracking approach combined with skin detection. Each newly detected hand is mapped to nearest user. This mapping is kept as long as the hand is visible to the system, thus leading to personalized hand detection, which is in turn used to assign each touch input to individual users by mapping each touch to the hand contour enclosing it. Touch points are recognized by an infrared multi-touch overlay, supporting up to 32 parallel points.

INTERACTION AND VISUALIZATION TECHNIQUES

In the following, we present an integrated set of interaction and visualization techniques that support the dynamics of mixed-focus collaboration on multi-view tabletops. All techniques rely on multi-touch gestures, which directly integrate with existing gestures on interactive surfaces. Views and transitions are controlled by multi-touch alone and are fully independent of the user's position and the head and body orientation. All techniques provide support for the main types of contents on interactive surfaces: full-screen contents and free-floating elements, as well as combinations of both. The techniques are also demonstrated in the video that accompanies this paper.

Fluid Transition between Group and Individual Work

The following two techniques support an easy and seamless transition between a group view that provides common ground during group work, and fully independent views during individual work for each collaborator. Permulin provides each collaborator with fully independent, visually overlapping, private full-screen views whereas previous

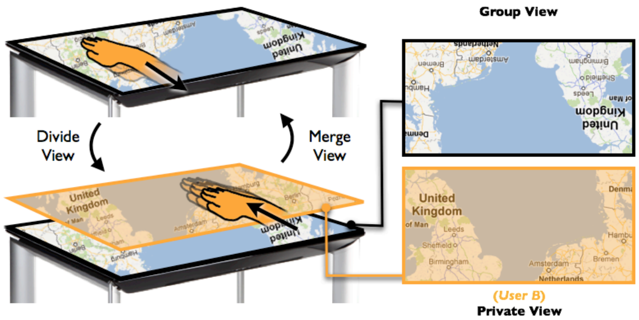

Figure 3. Enabling concurrent full screen collaboration

work on multi-view displays augmented the group view with private contents [8, 15].

Divide View: This technique transitions the group view to a private full screen view *only* for the user performing the gesture. Others remain in the group view. To do so, one of the collaborators performs a gesture that is inspired from grabbing the view: she places her hand flat on the surface and moves it toward her (see Fig. 3 top). Our implementation for two users creates a private full-screen views for each collaborator, each marked with a user-colored border. If necessary, the view is automatically rotated and oriented to the collaborator. Each private view can be seen and interacted with only by the respective collaborator. Initially, the private view is an exact copy of the group view. Subsequently, when collaborators individually modify their views, they become different. In consequence, all private views are fully independent and constitute high-resolution workspaces to conduct independent work unobtrusively and loosely coupled.

Merge View: A private view can be merged back into a common group view to support tightly coupled collaboration. To merge a view anyone of the collaborators performs a gesture that is inspired from releasing the view. It is similar to the divide gesture introduced above, but performed in the opposite direction (see Fig. 3 bottom).

The performing user then re-adopts the group view. Hereby private changes are integrated back to the group view. In case of conflicts (e.g. object changed by multiple users), the object is duplicated and only visualized in the corresponding user's private view with conflicts highlighted. From now on, all manipulations of the corresponding user are again mapped to the group view. Our implementation for two users transitions both users back from their private views to the group view when one of the users performs the gesture.

Awareness and Coordination during Individual Work

Phases of individual work are typically accompanied by moments of tighter coupling, where (portions of) individual workspaces are shared or highlighted, to support mutual awareness and coordination [26]. Previous work on multi-view tabletops did not account for sharing of private contents. We contribute two techniques, which support awareness and coordination through sharing and peeking.

Quickly and easily share private content: To share any portion of her private view with collaborators, the user performs a pinch gesture with both of her hands simultaneously, i.e. four fingers simultaneously, to avoid conflicts with conventional pinch-to-zoom gestures (see Fig. 4 top). This frames a shared viewing area, which becomes immediately visible to all collaborators as a window that is overlaid on their view. All collaborators can fully interact with content in this area. The owner can resize the area or maximize the shared view to full screen for sharing her private view in its entirety. Private elements, e.g. free-floating contents (e.g. overlapping photos), can be shared with other collaborators at any time by tapping a shared toggle button on the top right corner of the respective element and unshared by the same button again.

Peek into a collaborator's private view: In the reverse direction, a user can take a peek at another collaborator's private full-screen view (inspired by [2]) to e.g. quickly assess the work progress of the other collaborator without interfering with her individual work. Figure 4 (bottom) illustrates the technique: the three-finger gesture is inspired from temporarily pushing one's own view aside. This reveals the collaborator's view. If more than two users are present, the collaborator has to choose the target user in her private view. Permulin provides awareness thereof to the other collaborator by displaying an eye icon in her private view. A three-finger gesture in any horizontal direction brings the user back to her private view.

Reducing Interference in Group Views

When two or more users would like to interact with different shared elements that overlap in the group view, they are confronted with an access conflict. This becomes particular problematic when layered content cannot or only hardly be moved, e.g. pop-up windows in map applications.

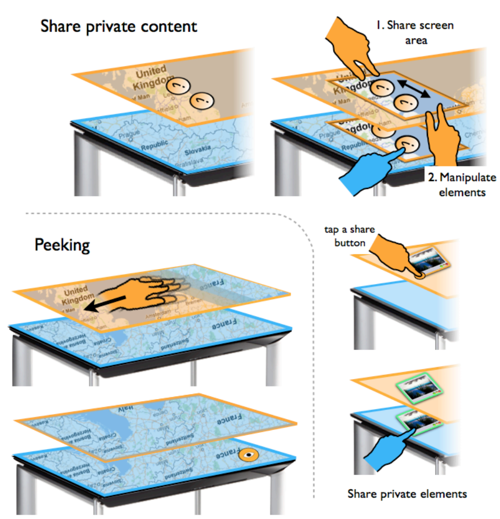

Figure 4. Concurrent interaction on private views

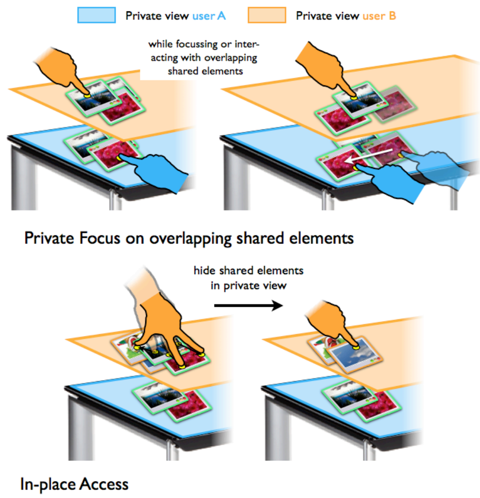

Figure 5. Concurrent interaction on the group view

Private Focus on overlapping shared elements: This technique allows users to concurrently interact with overlapping contents without losing the focus on the user interface element. Figure 5 (top right) illustrates this: to enforce a private focus on an element, a user touches and holds the element. The element is then visualized in the foreground in her private view. If multiple users perform this technique on overlapping elements, each of them sees the element they touch in foreground in their respective private view.

In-place Access: When content in the background is occluded by shared layered interface elements in the foreground, e.g. shared by a collaborator, users can hide these elements to reveal content in the background. Figure 5 (bottom) illustrates the technique: spreading out three fingers across a pile of foreground elements hides them and reveals underlying elements. The elements are only hidden in the user's private view, not in the group view. This way, collaborators are not disturbed. The reverse action, a three-finger pinch, brings hidden elements back to the fore.

EXAMPLE APPLICATIONS

Two example applications have been implemented to illustrate and evaluate the interaction and visualization techniques. The first one is a full-screen map application which provides route-planning functionality inspired by [26]. The second is a photo sorting application that enables users to co-create a photo collage. Both example applications constitute two highly relevant interface themes: interaction with (i) spatially fixed data, and (ii) free-floating interface elements. Both interfaces are illustrated in Fig. 6.

Map Application

The map application displays a full-screen interactive map in the group view that can be explored using conventional pan and zoom multi-touch gestures. The application provides two exemplary visual filters that can be overlaid over the map: a road traffic filter and also a Walkscore filter (cf. http://walkscore.com), to assess the walkability of a neighbourhood. The filters are visualized as resizable lenses on the map. A user can place a flag onto the map, indicating the starting position of a route, by tapping and holding. Placing further flags onto the map will create a route that connects all flags in a row.

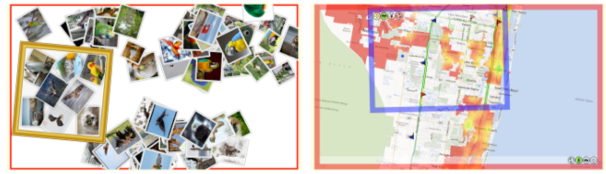

Figure 6. Example applications.

In case collaborators divide the group view, the maps in the private views are oriented towards the respective users and, together with both filters and flags, can be manipulated individually.

Photo Sorting

The photo sorting application visualizes a set of pictures as stackable elements laid out on the tabletop. They can overlap and can be individually manipulated through conventional multi-touch gestures to move, rotate and scale them. An empty frame, visualized on the group view, serves as a frame for a photo collage. Pictures can be dragged into and removed from the frame.

Collaborators can then either work tightly coupled with all pictures being visible. Or they can transition the group view to a private view, where the visibility of the pictures can be toggled through a button on each picture.

EVALUATION

We conducted a user-centric evaluation to assess the impact of the interaction and visualization techniques on mixed-focus collaboration on multi-view tabletops. The evaluation was a two-step process:

1. A qualitative study was conducted (a) to explore how participants used Permulin in different collaborative coupling styles and what their user experience was, as well as (b) to investigate physical interferences that might occur when users simultaneously perform touch input in overlaid private views.
2. These results informed a controlled experiment. Permulin was compared to a tabletop system and a split screen tabletop regarding (a) collaborators' use of space, (b) their ability to work in parallel and (c) mutual awareness; all across different coupling styles.

STUDY 1: QUALITATIVE EXPLORATION

Procedure

The participants were asked to collaboratively plan a trip using the map application, inspired by [26]. There were 5 tasks in total. First, participants had to collaboratively search for interesting places in a city of their choice: once without (T1) and once with (T2) the ability to split and merge views. Next, (T3) they started with split views and were asked to coordinate their planning activities from the prior tasks. Afterwards, they had to fulfil a new planning task, starting on the group view (T4). Last, they had to freely plan a city trip, again of their choice (T5).

There were 5 groups of 2 volunteer participants each (3f, 7m; avg. 26 years). Two groups, (P1, P2) and (P3, P4), consisted of close friends; (P5, P6) were friends from work and two groups, (P7, P8) and (P9, P10), were strangers. We chose a within-subject design. For each task, participants were given time to familiarize themselves with the system until they felt confident. Each group session lasted about 2.5 hours (think-aloud protocol, video-taped, interaction logs and semi-structured interviews after each task). After each session we transcribed the data, selected salient quotes and coded them using an open coding approach.

Results and Discussion

Support of Coupling Styles

All groups used to transition between the group view and the private views when the task setup allowed them to (i.e. in all tasks but T1) Particularly in T2 and T5, they spend long periods in the private views. Throughout the study, participants stressed that the private view helps them focus on individual tasks; as P3 put it: "I don't have to wait, I can just do my own things […] and the system helps me to focus on them". This is underlined by a strong sense of possession: participants described the surface as "*my* territory" (P5), "*my* virtual space" (P2) and "*my* map, and you [P8] have *your* own map" (P7).

Despite long periods spent in the private views, participants expressed a strong feeling of cooperation: "it was always about cooperative work" (P5, P6) and "although we worked individually, we still worked together" (P3, P4). The sharing technique was frequently used to let the other user know about one's own activities, e.g. about what they had found on the map. P7 commented: "it's easy to synchronize different views […]; it's just there, in front of you".

The peeking gesture was used by 7 users frequently, when the functionality was provided (except T1). Participants particularly appreciated the unobtrusiveness of the technique: "it does not end my individual work and does not interfere with my collaborator's work" (P7). Participants further pointed out that peeking allows for quick and easy coordination of their individual workspaces, e.g. P5 asked P6 to peek into her view, stating: "can you look at my view? I want to show you something".

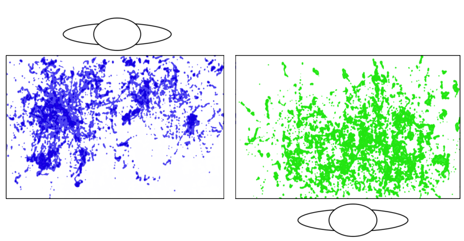

Figure 7. Accumulated touch logs aggregated for all participants for T2 and T5 (more intense color represents more touches).

However, three participants expressed some uncertainty about what their collaborator was able to see: "I didn't realize that you could see that [the map in T4]" (P10).

Physical Interference

We observed that participants frequently interacted in close proximity on the tabletop while they were working on their separate private views. Surprisingly, this did not lead to any notable physical interference, i.e. problems created by simultaneous touch input at similar locations. Participants stated, they "faded out the other participant's fingers" (P1) and that "fingers are not problematic, I didn't realize them" (P9). This finding is further backed by an interesting mismatch between our interaction logs and the participants' perception: The logs show that almost the entire surface had been used for interaction (see Fig. 7); however, all participants expressed the feeling they had interacted only in their proximity.

Summary

We assess the results of the explorative study as very promising: the overall user experience was that of a personal device during individual work and that of a highly cooperative device during group work. In particular, the phenomena identified in the analysis of the first study indicate that participants (1) quickly and easily switched between private and group views (particularly in tasks 2 and 5), allowing them to work in parallel, and (2) had a strong feeling of collaboration, also when working in the private views, and (3) experienced only little physical interference while using nearly the entire screen for interaction.

STUDY 2: CONTROLLED EXPERIMENT

The three major observations derived from the first study provide the basis for a more in-depth investigation of mixed-focus collaboration on multi-view tabletops. In particular, we investigated the following hypotheses:

H1: In co-located mixed-focus collaboration, Permulin provides a larger interaction area than conventional tabletops.

H2: Permulin supports highly parallel work, comparable to a split screen tabletop.

H3: Sharing techniques on Permulin to coordinate

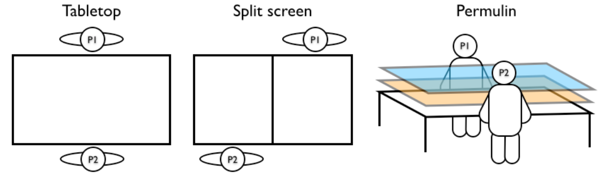

Figure 8. Different device types

workspaces are particularly used during mixed and loose coupling. More during mixed than during loose coupling.

H4: A user's awareness of where and what the other collaborator is interacting with and working on

H4.1: does not considerably vary across coupling styles on a multi-touch tabletop with a single view.

H4.2: does considerably vary across coupling styles on Permulin, enabling to transition between high awareness during group work and low awareness during independent work.

Setup

We controlled for three independent variables: the application scenario, the utilized device type and the coupling style between two collaborators.

As **application scenarios**, we used the two example applications described above. The example applications constitute two highly relevant interface themes: first, the map is a full-screen interface that contains spatially fixed data; moving the data implies moving the map which is likely to generate interference and second, the photos are free-floating interface elements that can be moved, rotated and resized on the screen and likely to be stacked.

Three **device-conditions** were compared (see Fig. 8) and were all run on the same hardware prototype: As baselines for comparison, we chose (i) *Tabletop:* a multi-touch tabletop (i.e. with a single view) and (ii) *Split screen:* a tabletop with spatially separated interactive spaces for both users. (iii) *Permulin*: a multi-view tabletop with the techniques and visualizations contributed in this paper.

Moreover, we distinguish between three different **coupling styles**: *Tight Coupling (Tight)*, working on the same problem; *Mixed Coupling (Mixed)*, working on the same problem with different starting points or constraints e.g. different pictures or different interests (filters) while planning a route; *Loose Coupling (Loose)*, working on completely different problems.

The dependent variables were: (1) Interaction on the interactive surface, i.e. number, location and time of touch contact, and (2) a user's awareness of where and what the other collaborator is interacting with and working on.

Tasks and Procedure

The study comprised two tasks (see applications in Fig. 6).

Photo Collage: The participants were asked to create a photo collage using the example application introduced above. At the beginning of the task, the participants were given one or two pre-defined sets of photos (50 photos each), visualized as a stack. The photo collage was considered finished when participants were satisfied with their results.

Route Planning: The participants had to plan a route using the implemented map application. Each participant had a lens that augmented the map with additional information (traffic and Walkscore). The task was considered completed, when the participants had found a route.

Table 1 gives a detailed overview over the concrete tasks for each coupling style. The coupling style determined the starting situation, i.e. whether participants were in private views or started with a group view on common ground. We crossed both device type and coupling style for each application scenario. In a pre-study, participants considered the use of a split screen setup in a tightly coupled collaboration unnecessary and equal to the traditional tabletop setting. Based on this feedback, we removed this condition from the main experiment, resulting in 8 subtasks per main task. The order of the tasks was counterbalanced using a balanced latin-square.

We chose a within-subject design and recruited 32 participants, each pair of them forming a group (i.e. 16 groups in total). Each of the groups was only assigned to one of the application scenarios due to time constrains. During each task, the participants were facing each other (as in [23]) and standing. All interactions were logged and video-recorded. After each task users were asked to fill out a questionnaire. Each session lasted 2.5 hours in average.

Coupling Styles	Photo Collage	Route Planning
Tight	**Data:** We provided a single set of pictures for *both participants*. **Task:** Participants had to design *one photo collage* together.	**Task:** Participants had to plan a *trip together* and find a compromise route between predefined start and end points, while planning to stop twice on the way for sightseeing.
Mixed	**Data:** We provided a different set of pictures for *each participant*. Each set had a predefined topic. **Task:** Participants had to design together *one photo collage* while each focusing on their specific topic.	**Task:** Participants had to plan a *trip together* and find a compromise route between predefined start and end points, while planning to stop twice on the way for sightseeing. Each participant had his *own constraint* that he was asked to follow (constraints were: traffic, walk score).
Loose	**Data:** We provided a different set of pictures for *each participant*. Each set had a different topic. **Task:** Participants had to design *their own photo collage* by themselves, while focusing on their own set of pictures.	**Task:** Each user had to plan a *route separately* between predefined start and end points, while planning to stop twice on the way for sightseeing. Both of the routes started or ended in the same area.

Table 1. Task description

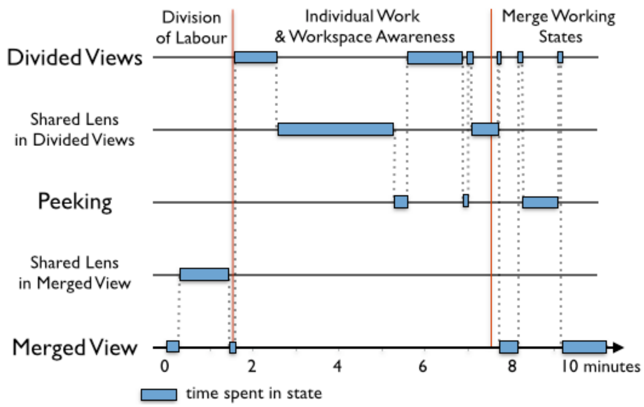

Figure 9. Exemplary illustration of a tight collaboration by one of the groups using Permulin.

Results

Interaction Area

The interaction area was measured as the average percentage of screen space each user was touching, accumulated and normalized over the task durations. It was calculated from the interaction logs. Across all conditions, the personal area was situated in front of each user with most interaction happening in its center and decreasing linearly towards the border of the screen.

The average interaction area was largest for Permulin (cf. Table 2), for both loose and mixed coupling in the photo task, as well as all coupling styles in the route planning task. A repeated measures ANOVA showed that the differences are statistically significant (Photo: $F(2,14)=13.12$, $p < .001$, Map: $F(2,14) = 4.43$, $p < .05$). Bonferroni corrected post-hoc tests revealed that the differences between Permulin and Tabletop are statistically significant ($p < .05$) in both tasks, the difference between the Permulin and Split screen condition was only significant in the photo task ($p < .05$).

Parallel Interaction

We calculated the average percentage of time (cf. table 3, relative to and normalized over the task duration) where both users touched the screen at the same time, i.e. temporally parallel touches within a time frame of 1s.

In both tasks, the differences between the Tabletop and the Permulin condition were statistically significant, as shown by a repeated measures ANOVA with Bonferroni post-hoc correction (Photo: $F(1,7) = 21.5$, $p < 0.01$, Map: $F(1,7) = 26.4$, $p < 0.01$). In case of the photo task, the effect size is small ($\eta^2 = 0.3$). However, the large differences between Permulin and Tabletop in the route planning task constitute a large effect size ($\eta^2 = 0.7$).

Coordination and Flexible Transitioning on Permulin

We analyzed how participants utilized the techniques for workspace coordination (peeking and sharing), as well as for transitioning between coupling styles (divide and merge) on Permulin.

Peeking and sharing: During loose collaboration, participants peeked in average 2.25 (SD 2.05) times (avg. proportion of time spent peeking 6.53%, SD 9.07%,) and shared their views an average of 4 times (SD 4.81). During mixed collaboration, participants peeked in average 1.25 (SD 1.85) times (avg. time spent peeking 5.58%, SD 8.26%) and shared their views an average of 5.62 times (SD 3.42). As to tight collaboration, participants peeked in average 1.12 (SD 1.64) times (avg. time spent peeking 2.98%, SD 5.42%) and shared their views an average of 7 times (SD 7.09).

Sharing photos was only possible in mixed and loose collaboration, since all photos were shared by default in tight collaboration. Participants shared 14.3 (SD 9.04) photos on average during loose collaboration. However, the photos were 99.2% (SD 0.9%) of the time only visible in their private views on average. For mixed collaboration, participants shared 26.1 (SD 18.58) photos on average, with being 94.55% (SD 5.31%) of the time only visible in their private views, on average.

Divide and merge: In loose collaboration, participants spent 100% of the time in divided views. In both mixed and tight collaboration, we identified two dominant collaboration themes: either groups spent most of the time in merged views or in divided views. In the case of mixed coupling, 6

	Tabletop	Split screen	Permulin
		Photo Collage	
tight	**45% (SD 14%)**	-	38% (SD 9%)
mixed	34% (SD 8%)	30% (SD 10%)	**40% (SD 11%)**
loose	35% (SD 9%)	33% (SD 12%)	**44% (SD 15%)**
		Route Planning	
tight	15% (SD 11%)	-	**26% (SD 10%)**
mixed	19% (SD 9%)	23% (SD 10%)	**24% (SD 7%)**
loose	25% (SD 12%)	21% (SD 8%)	**29% (SD 9%)**

Table 2. Average size of touch areas for both tasks.

	Tabletop	Split screen	Permulin
		Photo Collage	
tight	66% (SD 8%)	-	62% (SD 11%)
mixed	70% (SD 15%)	67% (SD 16%)	62% (SD 11%)
loose	78% (SD 13%)	73% (SD 18%)	72% (SD 7%)
		Route Planning	
tight	23% (SD 8%)	-	53% (SD 17%)
mixed	32% (SD 17%)	52% (SD 17%)	40% (SD 20%)
loose	21% (SD 15%)	74% (SD 10%)	66% (SD 19%)

Table 3. Average time participants interacted in parallel.

of 8 groups spent 94% (SD 11%) of the time in merged views, whereas the other 2 groups spent 92% (SD 3%) of the time in divided views. As for tight coupling, 3 of 8 groups spent 100% (SD 0%) in merged views, whereas 5 of 8 spent 73% (SD 13%) in divided views. The amount of time spent in divided views correlates (r = 0.7) with the amount of workspace coordinations (peeking, sharing).

Figure 9 illustrates the collaboration of one of the groups using Permulin in tight collaboration. Most of the time was spend in divided views. The collaboration started with a phase of division of labor, then transitioned to a phase of individual work. During this phase, sharing and peeking techniques were used to scaffold workspace awareness. Finally, the participants merged their working states using coordination and transitioning techniques.

Awareness

The awareness was assessed through a questionnaire after each experimental condition, inspired by [23]. The questionnaire consisted of two main parts: the first part (A1) assessed the participant's awareness of where and what the other collaborator was interacting with and working on. The second part (A2) asked the participant to estimate the awareness the other collaborator had of the participant herself. We thus interpret the results as the average amount of awareness cues a device provided to the user. The average results are shown in Table 4.

During loose collaboration, Permulin generated the least awareness cues in both tasks. The difference to the Tabletop and Split screen conditions is statistically significant (A1: $F(2,78) = 77.54$, $p < .001$, A2: $F(2,78) = 77.54$, $p < .001$) with Bonferroni corrected post-hoc tests ($p < .05$ for all differences). Also, Permulin generated statistically significant less cues during mixed collaboration, while both Tabletop and Split screen generated a high amount of awareness cues; as confirmed by a robust repeated measures ANOVA (A1: $F(1.77,69.08) = 41.24$, $p < 0.001$, A2: $F(1.77,69.08) = 41.24$, $p < 0.001$) with Bonferroni corrected post-hoc tests ($p < .05$ for all differences). Both Permulin and Tabletop generated a high amount of awareness cues during tight collaboration. However, the difference is not significant. As for the Permulin condition, the awareness increased monotonically from loose toward tight coupling, with all differences being statistically significant (A1: $F(1.98,77.21) = 47.61$, $p < 0.001$, A2: $F(1.99,77.55) = 43.04$, $p < 0.001$, and $p < .05$ for all Bonferroni corrected comparisons).

Discussion

When collaborating in a mixed or loosely coupled style, Permulin indeed provides significantly larger personal interaction spaces to the tabletop (H1). This holds even for tight collaboration on a shared full-screen element like a map. In turn, Permulin provides a more open and free interaction space on the very same screen. At the same time, Permulin enables a significantly higher degree of parallel interaction on shared full-screen elements than on the tabletop (H2). The performance is comparable to that of the split screen tabletop. In the photo task, participants interacted more often in parallel on the tabletop. However, the differences were only little and the effect size small.

	Tabletop	Split screen	Permulin
	A1: Awareness about where and what the other collaborator was working on (avg. for both tasks)		
tight	4.37 (SD 0.74)	-	3.86 (SD 1.32)
mixed	4.37 (SD 0.85)	3.39 (SD 0.97)	2.89 (SD 1.27)
loose	4.11 (SD 1.11)	1.90 (SD 1.11)	1.95 (SD 1.11)
	A2: Estimated awareness of the other collaborator of the participant (avg. for both tasks)		
tight	4.05 (SD 0.96)	-	3.61 (SD 1.30)
mixed	3.95 (SD 0.93)	3.41 (SD 0.85)	3.00 (SD 1.18)
loose	3.69 (SD 1.21)	1.87 (SD 0.97)	1.72 (SD 0.90)

Table 4. Average ratings awareness questionnaire (1 corresponds to low and 5 to high on a 5-point Likert scale)

Particularly notable is that participants frequently used Permulin's interaction techniques for dividing and merging views, as well as for workspace coordination (H3). This lets us assume that Permulin allows users to easily transition between the coupling styles, e.g. when quickly sharing a photo to discuss its importance and then either hiding it again to avoid screen clutter or including it in the collage. The latter is particularly apparent, since participants shared photos frequently during loose collaboration though being only visible in their private views most of the time.

The awareness does not considerably vary across coupling styles on the tabletop (H4.1) and is high for all conditions. The results further show that Permulin provides unique awareness properties: Permulin provides high awareness during group work and unobtrusive work with low awareness during independent work (H4.2).

SUMMARY

In this paper, we contributed Permulin, an integrated set of interaction and visualization techniques for multi-view tabletops to support co-located collaboration across a wide variety of collaborative coupling styles. Results from two user studies demonstrate that (1) Permulin supports mixed-focus collaboration by allowing the user to transition fluidly between loose and tight collaboration. The studies show that participants frequently used Permulin's interaction techniques for dividing and merging views, as well as share content to coordinate workspaces. (2) Users utilize Permulin both highly cooperatively but also individually. This is reflected by users occupying significantly larger interaction areas on Permulin than on a tabletop system, as well as performing highly parallel collaboration, particularly on shared full-screen contents. (3) Permulin provides unique awareness properties: participants were highly aware of each other and their interactions during tightly coupled collaboration, while being able to unobtrusively perform individual work during loosely coupled collaboration.

REFERENCES

[1] Agrawala, M. et al. The two-user Responsive Workbench: support for collaboration through individual views of a shared space. In *Proc. SIGGRAPH '97*, 327–332.

[2] Bolton, J. et al. A comparison of competitive and cooperative task performance using spherical and flat displays. In *Proc. CSCW '12*, 529–538.

[3] Gutwin, C. and Greenberg, S. Design for individuals, design for groups. In *Proc. CSCW '98*, 207–216.

[4] Isenberg, P. et al. Co-located collaborative visual analytics around a tabletop display. *IEEE trans. on visualiz. and comp. graphics*. 18, 2012, 689–702.

[5] Izadi, S. et al. Going beyond the display: a surface technology with an electronically switchable diffuser. In *Proc. UIST '08*, 269–278.

[6] Kakehi, Y. and Naemura, T. UlteriorScape: Interactive optical superimposition on a view-dependent tabletop display. In *IEEE TABLETOP '08*, 189–192.

[7] Karnik, A. MUSTARD: a multi user see through AR display. In *Proc. CHI '12*, 2541–2550.

[8] Karnik, A. et al. PiVOT : Personalized View-Overlays for Tabletops. In *Proc. UIST '12*, 271–280.

[9] Kiesler, S. and Cummings, J.N. 2002. What Do We Know about Proximity and Distance in Work Groups? A Legacy of Research. *P.J. Hinds & S. Kiesler (Eds), Distributed work. MIT Press*.

[10] Kim, S. et al. Enabling concurrent dual views on common LCD screens. In *Proc. CHI '12*, 2175–2184.

[11] Kitamura, Y. et al. A display table for strategic collaboration preserving private and public information. In *Proc. ICEC'05*, 167–179.

[12] Kitamura, Y. et al. Interactive stereoscopic display for three or more users. In *Proc. SIGGRAPH '01*, 231–240.

[13] Kulik, A. et al. C1x6: A Stereoscopic Six-User Display for Co-located Collaboration in Shared Virtual Environments. In *Proc. SA '11*, 188:1–188:12.

[14] Lissermann, R. et al. Permulin: Collaboration on Interactive Surfaces with Personal In- and Output. In Proc. *CHI EA '13* , 1533–1538.

[15] Matsushita, M. et al. Lumisight Table:A face-to-face collaboration support system that optimizes direction of projected information to each stakeholder. In *Proc. CSCW '04*, 274–283.

[16] Matusik, W. et al. Multiview user interfaces with an automultiscopic display. In *Proc. AVI '08*, 363–366.

[17] Mistry, P. ThirdEye: a technique that enables multiple viewers to see different content on a single display screen. In *Proc. SA '09*, 1–1.

[18] Morris, M.R. et al. Mediating group dynamics through tabletop interface design. *IEEE Computer Graphics and Applications*. 26, 5 (2006), 65–73.

[19] Peterka, T. et al. Dynallax: solid state dynamic parallax barrier autostereoscopic VR display. *In Proc. IEEE Virtual Reality '07*, 155–162.

[20] Ryall, K. et al. Exploring the effects of group size and table size on interactions with tabletop shared-display groupware. In *Proc. CSCW '04*, 284–293.

[21] Sakurai, S. et al. 2008. Visibility control using revolving polarizer. In *IEEE Workshop on Horizontal Interactive Human Computer Systems*, 161–168.

[22] Schmidt, K. and Simonee, C. Coordination mechanisms: Towards a conceptual foundation of CSCW systems design. In *Proc. CSCW '96*, 155–200.

[23] Scott, S.D. et al. Territoriality in collaborative tabletop workspaces. In *Proc. CSCW '04*, 294–303.

[24] Shoemaker, G.B.D. and Inkpen, K.M. Single Display Privacyware: Augmenting Public Displays with Private Information. In *Proc. CHI '01*, 522–529.

[25] Sugimoto, M. et al. Caretta: a system for supporting face-to-face collaboration by integrating personal and shared spaces. In *Proc. CHI '04*, 41–48.

[26] Tang, A. et al. Collaborative coupling over tabletop displays. In *Proc. CHI '06*, 1181–1190.

[27] Tse, E. et al. Avoiding Interference: How People Use Spatial Separation and Partitioning in SDG Workspaces. In *Proc. CSCW '04*, 252–261.

[28] Wigdor, D. et al. WeSpace: the design development and deployment of a walk-up and share multi-surface visual collaboration system. In *Proc. CHI '09*, 1237–1246.

[29] Wu, X. and Zhai, G. 2012. Temporal Psychovisual Modulation: a new paradigm of information display. *CoRR*.

[30] Xiao, Y. Artifacts and collaborative work in healthcare: methodological, theoretical, and technological implications of the tangible. *Journal of Biomedical Informatics*. 38, 1 (2005), 26–33.

[31] Zanella, A. and Greenberg, S. Reducing interference in single display groupware through transparency. In *Proc. ECSCW'01*, 339–358.