2023 IEEE 16th Pacific Visualization Symposium (PacificVis)

A Study of Zooming, Interactive Lenses and Overview+Detail Techniques in Collaborative Map-based Tasks

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2023 IEEE 16th Pacific Visualization Symposium (PacificVis) | 979-8-3503-2124-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/PacificVis56936.2023.00009

ABSTRACT

The support for multi-focus data exploration is vital in collaborative visualization. In these scenarios, which often involve multiple devices and large displays, users may focus on specific information on their individual screens while also sharing contextual views with others. While many visualization techniques developed for single-user applications can be adapted for use in collaborative settings, little research has been done on how to design adaptive versions of these techniques or how they may impact collaborative tasks involving large datasets. In this work, we perform a comparative study of three collaborative visualization techniques (Zooming, Interactive lenses and Overview+Detail) on large displays in three map-based visualization tasks (Exploration, Comparison and Spatial Memorizing). These three collaborative techniques draw on three different classical visualization techniques in a single-user setting. Our results show that these techniques have different impacts on users' task performance and preferences. The collaborative Overview+Detail technique benefits users most in supporting Spatial Memorizing. Closely coupled groups prefer collaborative Zooming in Target Exploration. Based on these results, we further discuss the design of collaborative visualization techniques and propose suggestions for adapting classical single-user visualization techniques to a collaborative setting.

Index Terms: Human-centered computing—Visualization—Visualization design and evaluation methods

1 INTRODUCTION

As the quantity and complexity of digital data continue to grow exponentially, data analysis is increasingly being performed in a collaborative manner. According to Cernea [11], teams are often best equipped to analyze and make informed decisions about these information-rich datasets. To facilitate collaborative exploration, new tools are needed to handle large amounts of data and complex tasks. A progressively increasing number of visualizations [21, 54] are being designed to support the collaboration of multiple users to combine their experience and analytical capabilities and build on each other's knowledge and potentially achieve more profound and valuable insights. However, current collaborative visualization approaches often involve a single user working with a single device or multiple users working with a shared screen, which can limit the effectiveness of collaboration. Users may be focused on their own devices, or one person may dominate the shared device, reducing the time spent interacting and communicating face-to-face. To enhance collaboration, new approaches are required to support multiple users to work together effectively.

There have been several new developments in the field of collaborative visual analytics that offer improved support. One of these developments is the proliferation of affordable large display technologies. Large displays can present a large amount of information, allowing multiple users to engage in sense-making and collaborative analysis [20, 50]. The high resolution of these displays, combined with the ability for multiple people to analyze data jointly, can improve the user experience and facilitate the effective use of visualizations [28, 51]. In addition to large displays, the development of small mobile devices has also been significant. It allows for computing to be untethered from a physical location, enabling people to discuss data anytime and anywhere. Furthermore, the combination of mobile devices and large displays has the potential to offer significant benefits in data exploration, as people can focus on their individual exploration on the small mobile device while sharing insights on the large display [35].

Several design questions need to be addressed to effectively support the multi-person collaborative exploration of multi-scale data using collaborative visualization on a shared large screen. These include questions about how to display information on multiple screens, how to support users in being aware of others' activities, and how to facilitate effective communication and collaboration. While typical visualization techniques such as Overview+Detail (O+D), Focus+Context (F+C), and Zooming (also called as Pan & Zoom) have been widely used for single-user exploration of multi-scale data [43, 47], there has been little research comparing their effectiveness in collaborative environments for different exploration tasks. As a result, currently it is not feasible to compile design guidelines for collaborative visualization in this context.

In this paper, we aim to investigate the effect of different adaptive collaborative visualization techniques in a large display-centric multi-mobile device setting for collaborative map-based tasks. We carry out a comparative study of three context-aware collaborative visualization techniques: Zooming (*Merge*), Interactive Lenses (*Lenses*) and Overview + Detail (*Split*) on three map-based visualization tasks (Target Exploration, Target Comparison and Spatial Memorizing). Based on the large 65" screen we are currently experimenting with, we have chosen a suitable collaborative team of 2 people for our study. These three tasks are the well-known basic tasks for map exploration. They can be combined into many high-level tasks, such as map data-based route planning, which involves target finding, comparison and location awareness of multiple routes/targets. Based on the results of the experiment, we discuss the design of these three adaptive collaborative visualization techniques and propose improvements to support collaborative data exploration on shared large displays. Our results not only provide design considerations and suggestions for collaborative environments involving multiple 2D devices, but also have relevance to immersive collaborative environments such as virtual, augmented, and mixed reality.

2 RELATED WORK

This section presents related work on visualization techniques for multi-scale data, interface design, and collaborative exploration.

2.1 Visualization Interface Design

Enabling the exploration of multi-scale data is a prevalent task in visualization. There are many well-established interface designs for separating and blending views [15] .

Zooming is a widely used method for exploring multi-scale

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DOI 10.1109/PacificVis56936.2023.00009

data [9]. The method is available in many interactive map applications such as Google Maps and Baidu Maps and other hierarchical aggregated visualizations [19]. It allows users to adjust their views and interactively observe data at different scales. Animation is often used to transition between the overview and the detail, but the context of the detailed view can still be lost.

Overview + Detail is a technique providing multiple views where details are presented in the main view, and the overview image is placed in the corners. It is widely used in applications such as maps [24], image editing tools, image collection tools [42] and computer games. The benefit of using O+D over zooming is that it allows users to easily switch between views without losing context of the information. Therefore, often the task completion time can be reduced [41] and user satisfaction can be improved [40]. However, O+D requires a dedicated area on the display which may potentially impede important information [45]. O+D is typically combined with zooming (as in the example of Google Maps [7]).

Focus + Context is a technique that allows users to inspect a small portion of the data (the focus) without losing a global view of the information space (the context) [24]. Usually, the focus view is embedded seamlessly in the context view, which shows the whole data in reduced detail so that the approximate position of the focused region is preserved [2]. Fish-eye views are often used to balance the area of focus and context and facilitate understanding of complex data; however, it may also cause intentional distortion [3]. Thus, although F+C decreases users' memory load, associated with assimilating distinct views of a system, it can cause serious information distortion issues, resulting in low reading comprehension [25].

Interactive Lenses is a technique that uses a circular widget (the lens) to show or emphasise a magnified region of the data [53]. It can be considered a type of F+C or O+D technique if the lens view is considered a dedicated visualization widget. The lens widget only appears when needed and does not cause distortion issues like F+C, but it may obscure an extensive area of the information space [4].

2.2 Visualization on Displays and Collaborative

Research has demonstrated that utilizing large vertical screens for visualization offers several advantages, including improved perception, a more immersive experience, the ability to compare data, improved spatial memory and the capability for detailed exploratory analysis [1,46]. With the increasing computing power and display capabilities of mobile devices, as well as advances in inter-device communication technologies, small and lightweight mobile devices are often used in conjunction with large screens to support data exploration [17,32,34,48]. This allows users to move freely and interact with the data from comfortable positions, reducing physical fatigue. Mobile devices can be used as input devices [17] or controllers [48] for large displays or as separate screens for presenting additional information or alternative visualizations in multi-device collaborative data analysis.

Collaborative visualization, which refers to the shared use of visualization by multiple users for a common exploration goal [27], generally improves user performance and results [27]. While many large-screen visualizations [8,26,30,33,43]support multi-focus data exploration, they primarily support it for a single user or multiple users using the same screen simultaneously without collaborating on a single task.

In conclusion, many comparative studies on visualization techniques have been conducted on standard-size monitors or in a single-person environment. Specifically, comparative experiments of different visualization techniques have focused on regular PCs [2,40,44,55], varying sized displays [47]. In recent years, there has been some work focusing on immersive environments [58]. These techniques have provided gradually adapted versions in collaborative/large display environments [5,14,23,29,34,59]. However, due to the lack of comprehensive comparative studies, no guidance has been offered on the appropriate visualization techniques for multi-device collaborative environments. Our experiment is conducted to address this gap.

Figure 1: *Merge*: (1) long-distance views, (2) close-distance views, (3) overlap views.

3 COLLABORATIVE VISUALIZATION TECHNIQUES

Our previous research [36] revealed that a fixed map displayed on a shared screen limits user engagement and interaction. As a result, we developed three flexible visualization techniques that utilize shared screens and multiple mobile devices to facilitate the exploration of multi-scale data. We exclude F+C in the study since it has been criticised by several previous works in single-person interfaces [47]. The spatial distortion in F+C could impair users' ability in judging relative spatial distances [15].

3.1 Design

We aim to determine how well-established single-user visualization techniques can be adapted to multi-device collaborative settings. We choose a multi-device environment with a combination of a large display and two small mobile screens as the starting point for our research. More specifically, our design allows for a clear separation between the public display and private displays for users. It uses a one-way data synchronisation process: individual mobile devices work independently without sharing information, and the large display synchronises changes from all mobile devices. Each individual viewport is highlighted by a coloured rectangle on the shared display. Dedicated colours are assigned to different users. Users are supported to scale the view on their personal devices using a standard set of actions, including pinch-to-zoom, panning the view through two fingers and marking a point through a long pressing on the display. The server handles the events and updates all viewports on the shared large display. This combination of large displays and small screens are believed to have great potential in benefiting collaborative mixed-focus data exploration and enabling efficient interactions to large displays compared to a single large display [12]. It allows users to work independently and attend other users' activities selectively, which is extremely important for collaborative exploration [18,39,49]. It can also reduce conflicts and prevent distractions and inference among collaborators.

Merge. The *Merge* technique (Figure 1) is designed based on the traditional geometric zooming technique in which users can zoom their viewports to switch back and forth between detail and context. Similarly, in the *Merge* technique, when users adjust their views on their individual screens, the shared display adjusts the viewport to show both users' views within a minimal rectangle. From *Merge*, users can easily notice the relative positions of other users. However, the shared display may not display the whole picture of the data, so users may lose the absolute position and full context on the area of interest. The shared viewport relies on both collaborators' interactions, which means that the change of the content showing in the shared display might be unpredictable to individual users. When the locations of user's views and the scaling factors are close, the large screen will present the details of both views clearly; when the two users' views are far apart, or when the scaling factor of the two views differs significantly, the details of one or both two views may not be fully rendered.

Split. The *Split* technique (Figure 2) is designed based on the concept of the well-established single-person O+D technique, incorporating its zooming capabilities while providing a unique perspective in both views. The shared display is split into two parts, showing

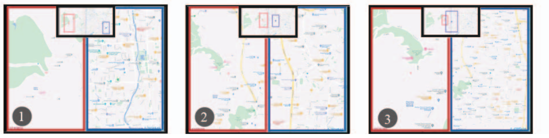


Figure 2: *Split*: (1) long-distance views, (2) close-distance views, (3) overlap views.

Figure 3: *Lenses*: (1) long-distance views, (2) close-distance views, (3) overlap views. the detail views are shifted when two views are close together.

two users' views for "detail" respectively, while an "overview" window is located at the top centre for the global context. The size of the "overview" window is set as 11.5% of the screen area, based on the setting used in a single-person O+D interface mentioned in Cockburn et al. [15]. When users adjust their views on their individual screens, the "detail" views on the shared screen will be updated accordingly and the "overview" window always shows the positions of both users' viewports. Thus, compared with the other two techniques, *Split* provides the biggest area for each user's view for "detail". Although the size of the "overview" window is small, it presents the absolute positions of all users' viewports, so that the user can always find the relative position of the other user easily. We assume that, with *Split*, users have a high predictability of changes caused by their interaction as the positions of all views are fixed, and users know where and how to find information.

Lenses. The *Lenses* technique (Figure 3) is based on the magnifying effect, displaying detailed views of specific areas selected by the user. It incorporates the zooming capabilities of similar single lens techniques. More specifically, the shared large display is initially used to show the global data. When users adjust their views on the individual screens, their viewports are marked as semi-transparent filled boxes (10% opacity, red or blue) on the large display (Figure 3). Dedicated windows are used to show details of users' views and are placed close to the viewports (the semi-transparent filled boxes). Each viewport's area is set as 10.5% of the total screen area, based on the setting used in the "lense" on a single-person interface mentioned in Carpendale and Montagnese [10]. Thus, *Lenses* uses the whole shared display to present the entire data. Compared with *Split*, it is easier for users to detect their absolute positions and the relative positions of other users in the visualization. However, the positions of the dedicated windows depend on the relative position of the focused viewports. Therefore, users may not be able to predict where detailed views will be located. Also, the magnified detail view causes a specific range of background information to be obscured.

To prevent overlap among viewports, we propose a shifting solution for positioning multiple lenses within a shared screen (see Figure 3) based on the method used in DragMag [57]. When the enlarged window does not overlap with any other window, it is displayed above the point of interest. When two points of interest are close together, the window is moved from its original position.

3.2 Implementation

The system is implemented using a server-client model, with a 65-inch large screen acting as the server and receiving user interaction events from two mobile phones (clients) controlled by separate users. An Android application on the mobile phones is used to connect to the server, and the view on the large screen is driven by the server, while the views on the mobile phones differ. The mobile phones capture touch events and viewport locations, and send the information to the server that handles all events. User interaction events from the clients are transmitted to the server over WiFi using an Android Socket connection. The client and server use socket communication. The server uses multithreading to receive connections from multiple clients simultaneously. The map preview and interaction are based on the Subsampling Scale Image View package, specifically designed for large file image previews.

4 EXPERIMENT

The experiment aims to fill the aforementioned gaps in the literature by investigating the effects of various collaborative visualizations (*Merge*, *Split* and *Lenses*) on users' performance and perceived workload in three collaborative tasks (Exploration, Comparison and Spatial Memorizing). We approached the study as a way to gain insight and understanding, rather than testing specific hypotheses, because previous research on comparing these three visualization techniques in single-user settings had inconsistent findings, and there was a lack of prior knowledge about how they are used in collaboration. Therefore, there was not enough information to form reliable hypotheses.

Participants. Our experiment recruited 9 pairs of participants (8 females) from a local university, aged between 20 to 27 (M=22.43, SD=2.31). Most of the participants were studying Computer Science. Three of the groups were students who knew each other before. All participants had normal or corrected to normal vision and reported prior experience with mobile devices (17 of them had three years of experience and the rest had at least one year). Four participants reported prior experience with large displays. All participants stated they were not familiar with the test city and had never been there before.

Tasks. Participants were asked to complete three tasks, including Exploration, Comparison and Spatial memorizing. Exploration tasks include searching and highlighting, while Comparison tasks include involve calculations, and comparisons. Spatial memorizing is a common task used in the exploration of map data. All three tasks are commonly used in map exploration [38], both in single user and collaborative environments [52].

Task 1 (Exploration): In this task, participants were asked to explore the map, tap and identify four predefined targets collaboratively, which means all the participants were required to mark all the targets. Both participants were required to find all targets (Figure 4(2)), for which they would explore, zoom and check details individually or collaboratively. As seen in Figure 4(1), the target list was given on the left. Once one participant found and marked a target on his/her device, the shared large display would show the mark on the map. Participants were encouraged to collaborate to find all targets as fast as possible. The task is stated as *"Please explore the map and identify all four listed targets on the map collaboratively"*.

Task 2 (Comparison): Participants were asked to count and compare the number of yellow icons around the two highlighted targets on the map. The two targets were pre-marked on the map (Figure 5(1)). Participants were asked to complete the task through the following steps: 1) move the view to the target area; 2) adjust the scale level to 1-1.05 (values shown on the corner of their view ports on the shared large display); 3) count the number of yellow icons in their own view frame; and 4) tap and confirm the target with more yellow icons surrounded by both participants. The participants had to check the view of the other participant to make sure the numbers were correctly counted. As a result, only the view which showed more yellow icons was required to be confirmed, as shown in Figure 5(2). A black point was displayed in the centre of the individual screen to aid the matching process, which served as a reference point. Similar to the previous works [13], we asked the participants to balance accuracy and speed and intentionally did not reveal the achieved accuracy after each trial to avoid a bias toward accuracy. The task is stated as *"Please zoom in to the same scale*

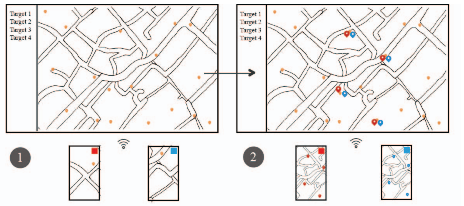


Figure 4: Task 1 (Exploration): (1) the large display shows the targets on the left side; (2) both participants need to find all targets.

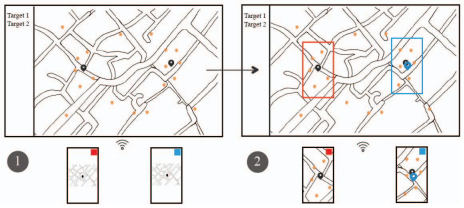


Figure 5: Task 2 (Comparison): (1) the large display shows two pre-defined targets; (2) participants need to find the targets; the participant whose view has more yellow icons taps the target on the mobile phone to confirm the task completion.

level (1 - 1.05), count and compare the number of yellow icons around the two highlighted targets on the map".

Task 3 (Spatial Memorizing): The aim of the task is to test users' spatial memory in collaborative context-aware visualizations. The precise presentation of relevant information is crucial in enabling us to communicate further and shift the stage of collaboration. As shown in Figure 6(1), a target's name (Target A) was shown to a participant (Participant A) on his/her mobile device. Each participant needed to search for the position of the target on the map displayed on his/her mobile device (Figure 6(2)). The correct position of the target would be marked on the shared large display after it was found. After both targets (Target A and Target B) were found by the two participants, six seconds would be given to them to remember the position of each other's target. After that, all marked targets would disappear from the large display (Figure 6(3) above). As the last step, a participant (Participant A) was required to find the other target (Target B) based on his/her spatial memory (Figure 6(4)). Please note that to ensure that participants can find the target, the name of the second target (Target B) would appear on (Participant A's) mobile device (Figure 6(3) below); however, it may take a longer time for them to search through names than searching based on spatial memory. The task is stated as *"Please find the target shown on your mobile device, then memorise the location of your partner's target, and find your partner's target on your mobile device."*.

The order of visualization techniques and trials presented for participants was counterbalanced to reduce the bias from learning effects. For each participant, we had $3\ (visualization\ techniques) \times 3\ (trials) \times 3\ tasks = 27\ trials$ in total.

4.1 Experimental Design

We tested our three shared large-display visualization techniques on three tasks using a quantitative within-subjects experiment.

Datasets. The data selected for this experiment is geographical data, a type of multi-scale data that is commonly used in collaborative visualization studies or multi-device applications. The maps used in our three tests were generated from Google Maps at a scale level of 16, which allows most street names to be visible. All potential targets on the maps are rendered as yellow. All maps are the same size and pixel ratio for each task, the aspect ratio is consistent with the larger screen, and feature cities are selected from China. The cities were selected based on their level of difficulty and the number of potential target points was standardized across all trials for each task to maintain a consistent level of difficulty. We used OpenCV to identify the potential target points to ensure consistency.

In Task 1 (Exploration), we kept the same number (N=100) and size of the yellow icons in all trials. In Task 2 (Comparison), the number of potential targets was set to a number around 150. The targets' names are invisible until being scaled to a uniform scale level. The yellow icons of all possible targets can be noticed from the default large scale. In Task 3 (Spatial Memorizing), the number of the possible target was kept at 100 for all trials. All potential targets were marked as yellow points, which could be easily noticed from the map, and the name could be seen from the same scale level.

Procedure. Participants were first introduced to the goal of the study. They were asked to read an information sheet and sign a consent form. After that, the participants completed the pre-test questionnaire about demographic information. Before the formal experiment, we introduced the task as well as the visualization techniques. We gave a brief demonstration of how the current technique can be used to complete the task. We provided training practice to the participants to get accustomed to the visualization techniques. Each trial was started by the experimenters and was completed when participants confirmed their choices on their devices. The completion time was saved in the system log. Through the experiment, the experimenters observed participants' interactions on the individual screens and on the large display, as well as their communications.

After completing all trials for each task on each technique, participants were required to fill in the post-test questionnaire (NASA Task Load Index [22]) that measures the perceived mental workload. At the end of the experiment, participants were asked to provide additional feedback on their experience on three visualization techniques, of which the experimenters recorded and took notes. Finally, participants were thanked for their time and feedback. The whole process of the experiment lasted on average about 1 hour.

Apparatus. The experiments were conducted using one large display (65″, 4096 × 2160 pixels, 60 HZ) and two mobile phones (6.39″, 2340 × 1080 pixels). In all techniques and tasks, participants were seated in front of the large display. The participants were freely positioned themselves in front of the large screen, between 60 cm and 100 cm in the experiment. Android Studio was used for the implementation of our collaborative systems. All surveys were hosted on LimeSurvey.

Data Collection. We collected measurements for time, accuracy, perceived workload, and interview responses from our participants. Time was measured in milliseconds from the start of the experiment until an answer was confirmed. Accuracy was measured as the ratio of correct overall answers. Perceived workload was evaluated using the NASA-TLX after participants completed all tasks with different visualization techniques. In interviews, participants were asked about their favorite techniques and strategies for solving tasks collaboratively, as well as how they communicated findings. The whole experiment was recorded in its entirety and analyzed by two trained observers, including the level of communication and coordination among the team, the distribution of tasks and responsibilities, and any issues that arose during the experiment.

5 RESULTS

We conducted tests of within-subjects effects using repeated measures analysis of statistical variance tests to discover any statistical differences in task performance, as measured by the completion time (faster being better) and accuracy rate (higher being better). An alpha of 0.05 was used for these parametric statistical tests. We performed the Shapiro-Wilk normality test to evaluate normality and found data (task completion time and accuracy) to be not normally distributed. Therefore, we used the Friedman test to evaluate the effect of these independent variables and Dunn-Bonferroni post hoc tests for pair-wise comparison. Effect Sizes (ES) was also reported.

Participants' subjective responses were collected via post-condition questionnaires and semi-structured interviews. The 7-point Likert-scale ratings collected from the questionnaires were

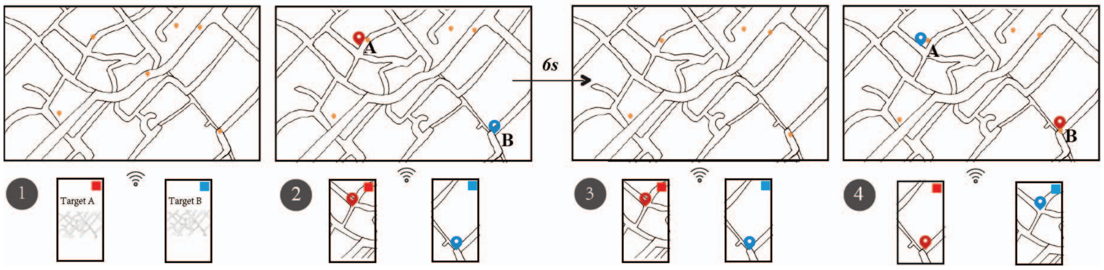


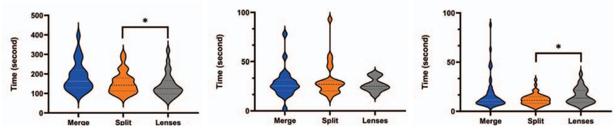
Figure 6: Task 3 (Spatial Memorizing): (1) the targets' names show on the individual screens, respectively; (2) participants search for their own targets and memorise the position of the other target; (3) six seconds after both participants find their targets, all marked icons disappear from the shared large display; (4) participants search for their partners' target.

analysed using the Friedman test when comparing visualization techniques. The recorded videowas reviewed to identify behavioural or conversational patterns and critical participant comments. The audio-recorded interview data were transcribed and a fundamental interview analysis was performed to determine how three visualization techniques impacted preference.

The data analyses yielded exciting results that reveal the characteristics of each visualization technique in each task. The quantitative and qualitative results are presented below and discussed in more detail in the following section.

Completion Time. Figure 7 shows the medium completion time for all three tasks. A Friedman test was carried out, showing that the collaborative visualization technique (*Merge* vs. *Split* vs. *Lenses*) had a significant statistical effect on task completion time ($x^2(2)$=7.630, p=.022) in Task 1 (Exploration). Dunn-Bonferroni post-hoc tests indicated significant differences between *Split* and *Lenses* (p=.019). Moreover, the differences between *Merge* and *Lenses* and between *Merge* and *Split* were not significant. The Kendall's W is 0.141, indicating a small effect based on Cohen's interpretation guidelines [16]. Therefore, from the results, we can conclude that participants, on average, were exploring faster in *Split*.

A Friedman test identified the difference among the three techniques ($x^2(2)$=.131, p=.937) was not significant in completion time in Task 2 (Comparison). A Friedman test identified that the difference among the three techniques ($x^2(2)$=7.912, p=.019) was significant in completion time in Task 3 (Spatial Memorizing). Post-hoc tests indicated significant differences between *Split* and *Lenses* (p=0.021). The differences between *Merge* and *Split* and between *Merge* and *Lenses* were not significant. The Kendall's W is 0.073. From the analysis, we can see *Split* supported the participants with better spatial memory.



(a) Target Exploration (b) Target Comparison (c) Spatial Memorizing

Figure 7: Task completion time (s) in three task.

Accuracy Rate. The accuracy rate is not applicable in the tasks of Exploration and Spatial Memorizing as only correct answers (correct positions of the targets) were allowed to be marked on mobile devices. Therefore, we mainly focus on the completion time of these two tasks. The accuracy rate for the task of Comparison (who has more yellow icons) is also computed. However, no significant effect has been found among the three techniques in this task.

Perceived Workload. We measured participants' subjective perception of effort using the NASA-TLX, which asks participants to rate mental and physical demand, overall effort, frustration, temporal demand and perceived performance on a seven-point Likert scale. The overall scores of three techniques on three tasks were shown in the Appendix. A Friedman test was carried out to compare the total score of NASA-TLX for three techniques. No statistically significant differences are detected among three techniques in Task 1 (p=.374), Task 2 (p=.071) and Task 3 (p=.273).

Preference. After the experiments, we asked the participants to choose the most effective technique for each task. As shown in Figure 8, in Task 1 (Exploration), 50% of the participants preferred *Merge* technique; in Task 2 (Comparison), 50% of the participants chose *Lenses*, while 40.44% preferred *Split*; in Task 3 (Spatial Memorizing), a considerably high percentage of participants (83.33%) preferred *Split*, while nobody chose *Lenses*. Chi-Square test identifies a significant statistical difference in the preferences among three tasks (p< .01), in Task 2 (p=.042) and Task 3 (p=.005). However, no significant statistical difference was detected in Task 1 (p=.062).

In addition, we encouraged participants to express their thoughts and feedback regarding the use of these three techniques. A summary of the main comments received is included in the appendix.

Figure 8: Participant's preferences in three tasks: Exploration, Comparison and Spatial Memorizing.

In the task of **Exploration**, for *Merge* and *Lenses* techniques, the most severe issue that the participants met was a distraction from others. Five participants reported that views on the large display were not fully controlled and those unexpected and sudden global changes can be disturbing and generate frustration. However, *Merge* was reported to be helpful by some users in filtering irrelevant information. *Merge* excels when teams need to work closely together, for example when one person has found a certain target and instructs another to find that point. For the *Split* technique, six participants reported that the two *Split* windows for displaying details occupied too much space on the shared large display. Another 6 participants mentioned that the "overview" window was too small to locate all views. We also noticed that, most groups (7/9) heavily relied on the oral instructions of the partners instead of finding targets directly from the large display.

In the task of **Comparison**, *Split* was most appreciated (7 participants) for its ease of operation being without interference. However, seven participants mentioned the issue of information obscuring, which means small view frames fixed in the upper centre position can cause interference in some tasks. For the *Merge* technique, five participants liked the clear presentation of information. However, four participants complained of dissatisfaction due to the influence of their partners. Both users control the viewport on the shared display — once one of the viewports is adjusted, the shared viewport would be adjusted correspondingly to ensure both users' views can be shown within a minimal rectangle.

In the task of **Spatial Memorizing**, *Lenses* received plenty of negative comments from those surveyed. The most cited problems include information obscuration, discontinuous display of information, inability to perceive the distance between two target points, confusion of information, and heavy distraction from others. *Split* received the most appreciation (n=8) for the clear presentation which helped with geographical information memorisation. When asked about their memory strategies, eleven participants relied on absolute positions and geographical features (such as a river) and the others (n=7) relied on relative positions and geographical features.

Collaboration. According to strategies described by users and notes taken by the observing experimenter, we summarised the main collaborative approaches in two collaborative tasks, Exploration and Comparison. We found during the collaboration that most groups first divided up the work, then worked in parallel and finally worked closely together to combine or analyse the information. So the users used the large screen first to get a general overview of the information and then divided the work; after that, each worked in parallel, mainly on their mobile devices, with the large screen as a supplement; and finally, when the information was aggregated after their respective tasks were completed, everyone's attention was focused back on the large screen. When something was found during the parallel work, a verbal reminder was given, and then the joint focus was on the large screen for the information analysis.

Also, more details of collaborative habits are revealed in Exploration: from the observation, we noticed that, according to the participants' collaboration strategies, the 9 participant pairs could be roughly categorised into two groups: closely coupled groups (3) and loosely coupled groups (6), drawing on Isenberg's definition [28]. For the closely coupled groups, once one participant found a target, he would report the position to the partner. Then, the partner would mark it immediately under the instruction of their partner. For the loosely coupled groups, the participants worked in parallel at the start and marked the targets found by the partner at the end. The three closely coupled groups of users were already familiar with each other before the study. Five participants chose *Merge* as the best technique in the task of Exploration. Besides, in *Merge*, most of the participants chose mobile devices as their primary tool for map exploration, while in *Split*, three participants chose a combination of the large display (for observation) and the mobile devices (for interaction). In *Lenses*, only one participant mainly used the large display to search for the targets.

6 DISCUSSION

The overarching goal of our studies is to answer the question, "How do these well-established single-user visualization techniques perform when adapted to some typical collaborative tasks and what needs to be considered when migrating these single-user visualization techniques to a collaborative environment?". Our results show that task performance, user preference and workload on these three techniques varied from task to task. In this section, we discuss the reasons for the differences under various task.

6.1 What leads to different performances for *Merge*, *Split* and *Lenses* in the task of *Exploration*?

From the results, as shown in Figure 7a, in the task of Exploration, *Split* was significantly faster than the other two techniques, followed by *Merge* and then *Lenses*. We believe a potential reason for this is that the *Split* clearly presents each other's markings all the time, allowing users to confirm the targets found by the other at any time without coordination with others.

In completing this task, each group had two general phases, a parallel exploration phase to independently search for target points in an agreed area, and a close collaboration phase to confirm each other's findings. In three groups, these two phases were constantly shifted; while the other groups completed their exploration first and then confirmed it. In the first phase, users communicated verbally to inform the names of the targets found and to prevent the discovery of duplicate targets. During this phase, the majority of participants (15/18) focused primarily on their own mobile phones, while the other three users' attention was mainly focused on the large screen. During the close collaboration phase, it was observed that the large screen was usually used to identify the location of target points found by their peers and then to guide each other to quickly find and identify target points. Therefore the visual display of different peer-marked targets on the large screen contributed to the differences in performance. The *Split* is the only interface that allows users to clearly view the targets that have been marked by the team at all times and without the need to coordinate with each other. When participants were told that their partner found a point, they would look up at the large screen to confirm whether the location was close to them and if so, they would quickly confirm it. If it is farther away, the user will confirm when they explore the nearby area. This behaviour was not well supported in other interfaces. In other two techniques, confirming each other's target points often requires the coordination of others' view.

Merge, using the smallest rectangle to include the views of both users, does not fully show all the marked points in the global picture. So finding the target point identified by the other person needs to be done by two people in coordination. The partner needs to move his view frame near the target point so that the large screen will clearly show where the other view is in relation to the position of the target point. Furthermore, although *Lenses* always presents global information, the enlarged information frame may cause information to be obscured. Coordination between the two participants was also often required when identifying each other's points. Thus, each pair of users often needed to coordinate views together to confirm target points that the other has found but not themselves, a process that undoubtedly increases the time taken to complete the task.

Why do more people choose *Merge* as their favourite interface? We speculate that it is due to the end-of-peak rule [31]. Since the favourite interface is a subjective choice, like many subjective feelings, it may be subject to the peak-end rule. This means that a person's subjective experience of what he or she is experiencing is primarily determined by the most intense experience and the experience near the end.

The final stage that the user worked closely to confirm the targets that the other person had found directly affected the user's subjective experience. However, this phase was shorter for the *Split* interface and longer for the other two interfaces. According to user feedback, *Merge* was the most effective for this phase. *Merge* was reported to be 'effective in filtering out a lot of irrelevant information', allowing the user to focus on the current location and the location to be confirmed. *Split*, on the other hand, using a miniaturised map to indicate both users' locations, was so small that users could only get a sense of the general location, so they had to jump to the collaborator's detail view when viewing details. This may cause some trouble for users. For the *Lenses* interface, in order for the user to see the point found by the other partner, the user needs to promptly move their view to a more remote place that does not interfere with the valid information and this process of constant adjustment has been complained by many users.

In summary, there were two phases in the first task: a parallel search for the target and close collaboration to confirm the target. *Split* always had a clear view of all the targets marked by the user. The user could confirm those nearby target points when the other user reminds them to find other target points, reducing the time spent in the close collaboration phase afterwards. This reduced the time it took to complete the entire task. The superiority of *Merge* in this task was that this technique effectively helped the user to filter much information during the close collaboration confirmation phase so that the user could quickly confirm the target with the help of the other partner. *Lenses*, on the other hand, did not have an obvious advantage in this task.

6.2 How *Merge*, *Split* and *Lenses* impact users' performances in the task of Comparison?

In the task of Comparison, there was no significant difference in the completion time , the accuracy and self-perceived workload. However, from interview, *Merge* technique was reported higher stress of the users than others. This task required the users to move the centre of their respective viewpoint to a defined position (marked on the large screen), adjust to a fixed zoom scale interval and compare the data around the two target points (counting the hotels). There were two phases in completing this task; the first phase was about navigating to one of the targets and then analysing the information around that target point; the second phase was to exchange information and reconfirm the information around each other's target points and then determine the choice.

Using *Merge*, users were unable to complete the first phase independently of each other. The user needed to refer to the position of the marked point on the big screen and move the view centre of the mobile to there. Furthermore, the viewpoint of the large screen will change globally when the other viewpoint changes. When two users adjust views together, they will be interfered with by each other. Many users in the experiment tended to navigate to the target point location in parallel first. They found that fine adjustments of the view would interfere with each other and then they adjusted the view in turn.

Split and *Lenses*, on the other hand, both guarantee the users to complete independently in the first stage and collaborate closely in the second stage. The reason for the difference in feedback between these two techniques is that *Split*'s overview frame caused occlusion, so some users had to take one more step - finishing the count on the large screen and then confirming it on the mobile phone. Thus the overall experience was a bit worse than *Lenses*.

6.3 What leads to different performances for *Merge*, *Split* and *Lenses* in the task of Spatial Memorizing?

The results in Figure 7c show significant differences in completion time in Spatial Memorizing and *Split* shows notable strength in supporting this task. In the interview, participants reported that they were memorising by the relative/absolute locations and geographic features (e.g. river). Since *Merge* shows maximal details of a specific area, we assumed that it could support users to recognize relative positions. However, based on the results that *Merge* did not speed up the time spent on completing the task, the relative location plus detailed information did not help in memorizing spatial positions.

We speculate that the information that users rely on was mainly absolute location-based and geographic features. *Split* provides the most effective help in this task. *Split* provides a completely clear view of the global information, as well as a clear display of the absolute position of both views in the complete view. At the same time, the detail view of *Split* also provides sufficient information about features, such as rivers, greenery and mountains.

On the other hand, *Merge* provides only relative position and details; *Lenses* provides absolute position but obscures part of the information about the target point location, resulting in a discontinuity of view information, so neither is good for memorizing.

7 MERGE+, SPLIT+ AND LENSES+

Based on these findings, we design and implement more adaptive versions with timing-based activation or deactivation of views for each technique in collaborative settings and provide suggesting tasks for each technique.

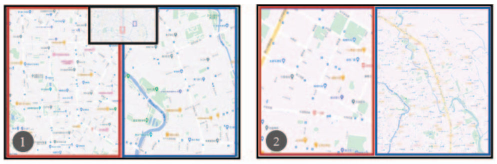


Figure 9: *Split*+: (1) when users adjust their views on their individual screens, (2) when users stop interactions for more than 5s.

Figure 10: *Lenses*+: (1) when users adjust their views on their mobile screens, (2) when users stop interactions for more than 5s.

1) ***Split+.*** In general, the advantages provided by the traditional "Overview + Detail" are obvious: *Split* provides both absolute and relative positions on the goal context; the "Overview" window is small but sufficiently clear; detailed information is presented clearly and the whole window provides a predictable visualization. These advantages result that *Split* achieving better results in Exploration and Spatial Memorizing tasks. The only issue found in the experiment is the possible occlusion caused by the small "overview" window. Thus, we propose *Split*+ (Figure 9). In *Split*+, the overview window will appear when users adjust their screen views. When users stop for more than 5 seconds, the overview window disappears to reduce possible occlusion.
2) ***Lenses+.*** One finding in the experiment is that the detail windows in *Lenses* may cover the original positions of the users' views (the transparent red and blue areas). Meantime, the frequent changes in the magnified detail frame cause the user's perception and awareness distress. Thus, we propose *Lenses*+ (Figure 10). In *Lenses*+, when users adjust their views on their screens, the magnified detailed frame disappears since we assume that users are more interested in their locations in the global context when they are interacting with their screens. When users stop for more than 5 seconds, the magnified frame appears and the transparent windows are displayed on the layer of the detail frame to indicate the locations of users' views.
3) ***Merge+.*** The original *Merge* is designed based on the "Zooming" effect, which provides a close look at the focused region. Through the experiment, we found its advantages in tasks requiring close collaboration, for instance, when social presence is essential to collaborative exploration. However, *Merge* does not provide a global context of the whole data and absolute positions of each view. Thus, we propose *Merge*+ (Figure 11) in which the overview window is presented in the top middle of the shared display. Similar to *Split*+, when users stop for more than 5 seconds, the overview window disappears to reduce possible occlusion.

In conclusion, when no action is detected on mobile devices for 5 seconds, it is assumed that users are viewing details or comparing information on the shared screen. To facilitate this, information occlusion should be minimized as much as possible. Thus, the overview window will disappear in *Split*+ and *Merge*+. Additionally, *Lenses*+ has been designed to to support users comparing details by making detail windows appear on the shared screen when no action is detected. Our experiments showed that a five-second delay can strike an appropriate balance between smooth interaction and collaboration. However, further research with a larger and more diverse group of users is recommended to evaluate the impact of time delays fully.

Furthermore, in order to learn the usability of the improved de-

Figure 11: *Merge+*: (1) Participants manipulate the view on their mobile screens, (2) Participants do not manipulate the view over 5s.

sign, we conducted an informal user evaluation with three former participants. All of them were very positive about the improvements made to the visualization and reported that the new features made the techniques much easier to complete visualization tasks. Users specifically noted that the delay for *Lenses* made the information less cluttered than the previous design.

8 GENERALISATION AND LESSON LEARNED

Generalization. Among 18 participants, sixteen students were in HCI/VIS. They all had a basic knowledge of the use of interactive systems. Three of them were postgraduate students and the other thirteen were senior students at our university. We reflected that their backgrounds might help remove obstacles once they interact with the designed systems. This would help other researchers in HCI/VIS field to recruit participants for similar research; however, we also realised that other components might contribute to uplifting the success of collaborative visualization, i.e., real-life experience, including immersive games and simulation-based work training. Although we did not investigate similar components in our study, we suggest others consider those components.

In addition, three tasks, widespread in geographic data, were used to test these three visualization techniques. Users were given a training session to familiarise themselves with the interfaces and functions; then, three studies were completed for each of the three interfaces; the workload was evaluated after each job was completed for each interface and a semi-structured interview followed the questionnaire to understand their feelings and preferences. In line with the above background investigation, familiarising the experimental tasks and environments is vital. Since collaborative visualization is new to participants, a systematic process to engage participants will fruitfully strengthen the quality of the practical work.

In this work, the impact of the three visualization techniques on users was measured from various aspects, including task completion efficiency, accuracy, users' self-perceived workload, users' subjective post-task comments and observation notes during the experiment. From the collected data, the results of the ranking of users' preferences (Figure 8) and the ranking of users' self-perceived stress are highly consistent and are also roughly consistent with the ranking of the speed of completion time (Figure 7). Also, the visualization method with more negative comments in the interview has a high probability of causing lower task efficiency with a more significant workload. Therefore, the data from all parties corroborate each other and show more clearly the advantages and disadvantages of each visualization technique for different tasks.

At the same time, many participants said that 'the task was interesting and inspiring for his experiments afterwards'. One user mentioned that "although it is a simple task, it is a very clever simulation of the process that sometimes requires multiple parties to collaborate to complete real complex tasks". Another two users reported that "this task is very much like the usual group work, where someone is always slow and needs assistance from others".

Lesson learned. We have gone through design circles, developing, testing and modifying the design. It was fascinating to see how three visualization techniques influence users' performance and experience. We share the lesson learned from the present study.

- Changes to the shared large screen should be highly predictable for both users. Since changes on the shared large display can be triggered by different users; these changes should not have the potential to cause disorientation (such as when a change from a user disturbs what the other user is looking at). This means avoiding techniques that trigger the global changes on shared view. Where techniques that normally do this (such as translation or zooming) are needed, the display space can be divided into distinct areas for each user. This can be done using techniques such as *Split* and *Lenses*.
- For tasks that require closely coupled working, the design should avoid dividing the display space between users. *Split* and *Lenses* which present the multiple focus in different windows are considered less effective when users are in a closely-coupled phase of work (e.g. at the end of Exploration when participants were instructing each other to confirm the missed target). This is because at this stage users tend to communicate frequently in the same area. Shifting between different windows to access necessary information increases the perceived pressure on the user.
- When single-user visualization techniques, such as O+D and Lenses, are migrated to a collaborative environment, many design parameters should be adaptable to the collaboration mode. For example, currently the size and location of the overview and detail windows are designed with reference to parameters that are mostly suitable for a single user environment. However, in practice, it was found that fixed values could not meet the needs of all tasks. A more intelligent design that meets the changing needs of collaboration is expected.

In the discussion above, more than those technical contributions, four reflections which we believe shape our thoughts profoundly, directing our possible research interests for the near future.

Visualization Techniques. Our study compared the Zooming, Interactive lenses and Overview+Detail in collaborative data exploration. Those are the most widely-used techniques and are likely to be among the first choices when designing interfaces for collaborative data exploration. Thus, we believe our selected procedures cover a wide range of interaction techniques for collaborative data exploration and provide practical guidance on choosing the most effective and applicable method. Our study is the first attempt to assess the visualization technique for collaborative data exploration and analysis in a multi-device environment. This is fruitful because, to our knowledge, utilising proper courses to support collaboration in visualization tasks is brand new. Our methods make it possible for the HCI/VIS researchers to get inspiration on enlightening and even groundbreaking knowledge to explicitly design techniques for supporting visualization in a team manner promptly.

The Size of the Focal Area. We chose the parameters of the lens to ensure that users could interact with the zoomed-in portion of the map while other users could still see the context on the screen. The detail within the focal area on the large screen is currently consistent with that on the mobile phone. When the shared large screen size is more extensive, we can experiment with different focus sizes to explore the impact on the user experience. In the overview+detail technique, where we split the screen in two, we intentionally scale the size of the detail box to align with the view on the mobile side to reduce confounding factors for the user so that some space is wasted on the left and right sides of the large screen. We assert that it is worth testing how the interface separation of the large screen is split once more than three collaborative environments are involved (whether the same proportional view frame is maintained or not).

Data and Tasks. Our studies tested geographical data, one type of widely used data. Our tested tasks focus on the data to explore, navigate and compare and memorise. These tasks were chosen to investigate the tested conditions' effect on users' performance. The tasks we have decided to try so far are three separate, simple tasks that purposefully try the version of three different visual interfaces on three representative types of functions. This directs that more sophisticated and high-level collaborative tasks like map-based planning or layer comparison for map [37], which should be expected in the future to achieve solid experimental results. However, the complexity of data and types will affect the results in sophisticated studies. We foresee that carefully selected complex data (in conjunction with real-world application scenarios) will be needed; otherwise, the testing results could be less representative. That can cause the collaborative visualization to be less reasonable to users.

Multi-device Settings. In collaborative environments that combine large and small screens, we have found that users rely heavily on mobile devices for relatively parallel and independent tasks, and frequently use the large screen to check each other's working progress or to compare the information. Previous research has raised concerns that the incorporation of mobile devices into a collaborative environment could lead to reduced awareness of collaboration [56] and reduced communication [6]. However, we found these issues would not be prominent when the collaborative visualization (information and progress) was fully synchronized on the large screen.

The Shared Large Screen and Multiple Users. In our study, we focused on exploring the impact of different visualization techniques rather than the impact of the device or the group size. Therefore, we only included a setup where two users shared a 65" screen. We chose this screen size and number of users based on user experience, as we found that two users standing in front of a large screen of this size was appropriate. In a pre-test, we found that having three people standing in front of a large screen would be crowded and the space allocated to the screen would make it feel like the shared screen would be of little use. However, we are interested in how our visualization techniques would perform on larger screens, such as a 95" screen or wall display, and with more users. While conflicts may arise more often when our techniques (such as *Merge*) are used in large group collaborations, we believe that these these techniques can be adapted to better support such scenarios. For example, in collaborations involving more than two people, *Merge* will not be a view that combines everyone's views. We can instead provide mechanisms to combine the views of 2-3 users who are working closely together. Overall, we believe that larger screens and environments where more people can collaborate can be a promising direction for those interested in similar collaborative visualization techniques.

9 CONCLUSION

We conducted experiments to test the effect of different collaborative techniques (*Merge*, *Split* and *Lenses*) on three map-based tasks (Exploration, Comparison and Spatial Memorizing). Our evaluation reveals that the visualization technique employed profoundly impacts the users' performance and preferences in different ways. *Split* combining overview and detail view was found to benefit users by supporting tasks involving spatial memorizing. *Lenses* and *Split* techniques required less effort for tasks involving comparison. *Merge* (zooming to the smallest combined viewport) was preferred by groups working more closely-coupled for tasks involving target exploration. Based on the evaluation results, we also propose more adaptive versions of these techniques for collaborative settings and provide suggestions for supporting collaborative data exploration on shared large displays. These findings extend our understanding of the design of collaborative visualization techniques and provide a foundation for designing techniques that can support a broader range of collaborative visualization systems.

ACKNOWLEDGMENTS

The work was supported by NSFC (62272396, 62207022) and XJTLU RDF(22-01-092, 19-02-11).

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