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ORIGINAL ARTICLE

VisPorter: facilitating information sharing for collaborative sensemaking on multiple displays

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Abstract The multiplicity of computing and display devices currently available presents new opportunities for how visual analytics is performed. One of the significant inherent challenges that comes with the use of multiple and varied types of displays for visual analytics is the sharing and subsequent integration of information among different devices. Multiple devices enable analysts to employ and extend visual space for working with visualizations, but this requires users to switch intermittently between activities and foci of interest over different workspaces. We present a visual analytics system, VisPorter, developed for use in a multiple display and device environment, and a user study that explores the usage and benefits of this system. VisPorter enables seamless cross-device activity through lightweight touch interactions, and allows multiple displays and devices to be fluidly connected for sensemaking.

Keywords Display ecology · Collaborative sensemaking · Visual analytics · Text analytics · Multiple displays

1 Introduction

Our modern environment is filled with various communication and computing devices including smartphones, tablets, laptops, desktop workstations, and large high-definition displays. Such devices that vary widely in interactivity, capabilities, and affordances present new opportunities for data analysis and visualization.

Several benefits and characteristics can be derived from interactive workspaces using multiple displays and devices. The fact that multiple displays provide physical spaces beyond one single virtual raster space enables users to: (1) increasingly utilize space as a resource for visual perception and spatial ability [1], (2) extend the device they are currently using to any nearby devices as needed, with appropriate technology [2, 3], (3) tap into the potential of different types of technologies for suitable tasks or data [2, 4], and (4) collaborate more flexibly by satisfying the analytic needs of multiple users in a group through multiple devices [5].

These benefits are directly related to the spatial, opportunistic, and collaborative nature of multi-display environments. Multiple displays enable analysts to employ and extend visual space, but require users to switch intermittently between activities and foci of interest across different displays. Thus, one of the significant inherent challenges that accompanies the use of multiple types of displays for visual analytics is the requirement for seamless cooperation and coordination of displays and devices into a unified system for sharing and subsequent integration of information and analysis tasks [6]. There has been an ample amount of previous research that enables cross-device interaction in multiple display environments [7–10] but little work has focused on directly supporting visual text analytics for collaborative sensemaking in which multiple users can spatially and opportunistically transit and organize their analytic activities, documents, and visualization across displays.

To address these issues, we present VisPorter, a collaborative text analytics tool directed toward supporting sensemaking in multiple display environments in an

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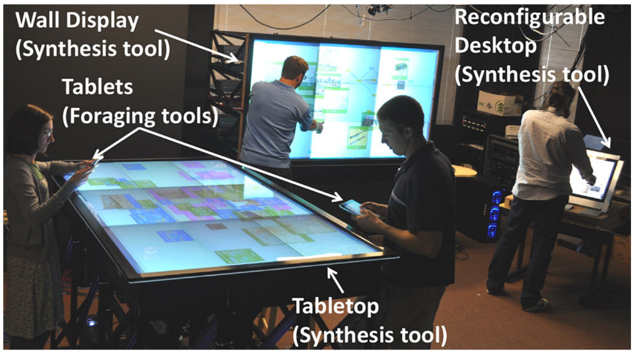

Fig. 1 VisPorter is a collaborative text analytics tool for multiple displays

integrated and coherent manner (Fig. 1). Through lightweight, spatially aware gestural interactions such as "flicking" or "tapping," the system allows multiple users to spatially organize and share both information and concept maps across displays. It provides a suite of multiple sensemaking tools with which users can forage for information, and make sense of and synthesize it to form hypotheses collaboratively across multiple displays. We conducted an exploratory study to investigate how such a multi-display workspace, which allows users to distribute information and visualization across multiple displays, can impact the strategy and process of collaborative sensemaking and to evaluate our proposed design principles for seamless multi-device systems.

2 Related work

Little guidance can be found in the literature on the design of integrated multi-device systems that allow for transparent cross-device information sharing. Existing guidelines related to single and multiple display systems may still apply, but it is highly probable that distinctions and nuances that we explore in this work need to be adapted for a cohesive multi-device sensemaking system. We derive our initial design for VisPorter from visual analytics, collaborative visualization on novel displays, and interactive spaces based on multiple displays.

2.1 Visual analytics

We combined features of visual analytics for single display systems to support various text analytic activities on multiple displays. "Sandbox" in the nSpace suite is designed to support an open workspace where users can move information objects and organize on the display space for external representations [11]. Andrews et al. [12] expanded the benefits of the external representation to sensemaking tasks on personal large displays. Their tool emphasizes spatial organization of various documents and entities, enabling the analyst to leverage the larger screen space for rapid externalization of their cognitive syntheses during the sensemaking process. VisPorter was motivated by these systems in spatially organizing hypotheses and evidence to better leverage the larger and more diverse space created by multiple displays. VisPorter was also motivated by "Jigsaw" [13] in that it provides visual illustrative connections between automatically extracted entities in multiple documents. "VizCept" supports capabilities for merging multiple users' findings, allowing for collaboratively creating concept maps and timeline visualization in real time [14]. VisPorter extended VizCept's collaborative creation of concept maps on individual displays in multi-display environments. In these visual analytics tools, sensemaking is mostly confined to the single shared space on the individual screen, but VisPorter allows users to distribute and organize data and sensemaking tasks across multiple displays.

2.2 Collaborative visualization on novel displays

New visual analytics and visualization systems based on non-traditional shared screen spaces have begun to support co-located collaboration for visual analytics. For example, Cambiera enables multiple users to search and manage documents through its unique widgets and allows them to organize documents on the tabletop [15]. Tobiasz et al. [16] developed a system called "Lark" that lets multiple users analyze the same data with visualizations on a single tabletop. Hugin focuses on enabling multiple remote users to synchronously interact with shared visualizations [17]. Conversely, VisPorter is designed for co-located synchronous collaboration and allows users to combine several personal concept maps from multiple displays, rather than simply interacting with each visualization remotely. Similar to VisPorter, the branch-explore-merge [18] approach allows multiple users to modify information on individual displays privately and then merge their changes onto a shared display upon the agreement of other group members. However, in contrast to VisPorter, only the same formatted geospatial information is displayed on the shared display as well as on the individual devices. Jetter et al. [19] presented Facet-Streams, a collaborative search tool that allows users to combine multiple search features with a tangible user interface in order to filter a dataset. It utilizes multi-touch interaction and tangible tokens placed on a tabletop to display multiple filter streams that can then be combined into single streams to view the filtered data. VisPorter shares similar concepts through throwing and combining individual concepts and concept maps to relate individual thoughts to a global concept. While these emergent visual analytics and visualization systems represent a remarkable improvement over past models of users working on isolated devices without access to a common view of information, they are nevertheless limited to a single visible display and all user interactions and sensemaking remain confined within it.

Results of some user studies inform design implications for VisPorter. Vogt et al. [20] and Isenberg et al. [21] adapted existing visual analytics tools for multi-user interaction on large display environments. Isenberg et al. [22] addressed the types of collaboration styles that are adopted during co-located collaborative visual analytics on a single tabletop. These studies highlight the importance of flexibility in collaborative interaction.

2.3 Multiple display environments

We are inspired by Streitz et al.'s [9] i-Land vision of a room where users can mix-and-match multiple portable and large displays and devices. Zoomable object-oriented information landscape (ZOIL) is a multi-display zoomable user interface framework, where each display offers a view into a common zoomable space, tangible lenses or other tangible objects can be used to control or synchronize the views [1]. Geyer et al.'s [23] system uses ZOIL to enable collaborative sketching on multiple displays. Whereas, VisPorter emphasizes independent display spaces across which analytic tasks can be distributed according to the affordances of the devices and information objects can be transferred using lightweight touch interactions.

A few multi-display systems focus on screen sharing to enable users to share their private laptop windows onto larger shared displays. Also, input redirection enables users to interact with the shared windows by using any of the devices (private or shared) for input [24–26].

Some multiple display systems provide interactive techniques for transferring information across different devices for sharing with other collaborating users [27, 28]. For example, with i-Land, users can associate digital objects with physical tangible objects, which can then be used to move the objects between computers. Pick-and-drop [29] uses uniquely identifiable interaction devices, such as pens, to transfer digital objects between multiple displays. Dachselt et al. [30] and Marquardt et al. [31] explore cross-device interaction techniques which enable users to tilt devices toward one another for sending information. Whereas, VisPorter supports spatially aware touch gestures to move information objects (see Sect. 4.4). In Wigdor et al.'s [32] system, each display has a world in miniature (WIM) view of the other displays, through which users can drop or retrieve digital objects to transfer them between displays. VisPorter shares a similar metaphor, in which a visual proxy can represent the spatial location of a mobile device near another surface to provide a spatial destination for transferred objects during spatially aware gestural inputs.

In contrast to stationary multiple display setups, some systems allow users to customize views spatially. For example, Spindler et al. [33] presented Tangible views which are cardboard interfaces created using overhead projections in conjunction with a tracking system. This system allows users to take advantage of physical space and skills by directly moving the cardboard lenses to interact with a large visualization on the tabletop (e.g., focus + context, magnification of a piece of the whole visualization, etc.) but visual results cannot be taken away from the projected images on a cardboard lens. By using cardboard, the visualization and information disappears when the tangible view is removed from above the tabletop display. Thus, users' analysis activities are confined to the space above the tabletop display.

2.4 Summary

VisPorter focuses on collaborative visual text analytics and enables users to distribute sensemaking task artifacts including documents, images, entities, and visualizations into the physical space on the various displays and devices. Our goal is to extend the concepts of "space to think" [34] to multiple displays with cross-device interaction, so as to enable users to further externalize their syntheses in such a way that the physical space composed of multiple displays and devices takes on semantic meaning within the context of the users' sensemaking process. Our emphasis is on the potential benefits to be gained from allowing sensemaking to occur within an "ecology of displays and devices" where all the devices in the environment develop roles and relationships.

3 Design principles

Sensemaking plays a key role in the analysis and decision-making processes involved in sifting through vast amounts of information. It is defined as a process in which pieces of information are collected, organized, and synthesized in order to generate a productive conclusion and to initiate new questions or lines of inquiry [35]. Based on findings and design considerations from several prior related research projects in visual analytics, sensemaking, large displays, and multiple display environments, we generated four design principles (D1–D4) to guide our design of VisPorter:

D1 Exploit physical space through physical navigation and persistence:

Physical space is essential in sensemaking since we are embodied beings who experience and live in physical, tangible worlds [36]. For example, Ball et al. [37] showed physical navigation produced a performance improvement in visualization tasks over virtual navigation. They proposed several design suggestions to encourage physical navigation in the design of visualization systems, reducing dependency on virtual navigation. Multiple displays enable users to carry and analyze pieces of information among multiple displays populating the physical space. Persistence can also be a key design consideration that enables users to better exploit large physical space [20, 34]. Persistence affords continued visual availability of information and documents. Based on the concept of persistence, Andrews et al. [34] and Robison [38] suggested integrating sensemaking tools into the document spaces in which users freely arrange documents into spatial structures based on their content such as clustering or ordering.

D2 Share visual information objects in a direct and physical manner:

Generally, access and management of dispersed information across multiple devices is a major problem in multiple display environments. For an integrated multi-device system, users should be able to share and analyze information objects and visualizations in a direct and intuitive manner, solely focusing attention on the direct physical reference of the material being handled (e.g., a particular document, entity, and image) rather than by nominal references such as document ID, filename, or URL. Nacenta et al. [8] also showed spatially aware interactions are useful to transfer data between devices maintaining focus on the material being handled. Chu et al. identified five design themes that relate to how multiple devices may help students' thinking processes by objectifying information [39].

D3 Spread and organize tasks, data, and visualization across displays:

Devices should independently allow for the maintenance of data, workspaces, and analysis activities based on display form factors, while ensuring that the end results of personal analyses and data sources are incorporated into the final unified results. For instance, the multi-device system should facilitate both individual analysis and synthesis tasks, as well as seamless transitioning between tasks. Vogt et al. [20] provided a few design suggestions for co-located collaborative sensemaking using a large shared display, and found that collaborators frequently preferred different analytic approaches, sometimes requiring different devices. Geyer et al. [5] also suggested that different activities such as individual or collaborative tasks should be supported by suitable devices and modalities.

D4 Support dynamic device membership and spatial interawareness:

Users should be able to reorganize the analytic workspaces across displays freely based on changing needs, and to deploy and span analytic tasks across the different types of displays available. Therefore, the necessity for such an inter-relation of devices and user activities implies that a flexible interoperable infrastructure supporting dynamic device membership in multi-display environments is a must. It can be supported through a plug-and-play model that enables the user to pick up, mix and match devices, tasks, interaction techniques, and data. With such an infrastructure, all displays enable continuous support and capture the insight formation process as it may occur in any display or over time in the large information space.

The above design principles, derived from the literature and insights from our own past sensemaking research projects, formed the foundation of our design choices during the development of VisPorter. We reference the principles throughout the rest of the paper to describe the system proper, and how they supported, hindered or modified users' behaviors with the system during the study.

4 The VisPorter system

VisPorter is primarily designed to gain collaborative insight into a large number of text documents by sharing, transferring, and spatially organizing digital objects in multiple format types and multiple visualizations across displays. It also supports synchronous, collaborative creation of concept maps from a set of important keywords across different displays. In the following sections, we illustrate how we designed the tools and interfaces of VisPorter through a use case scenario and then we describe the tools and important capabilities of VisPorter in greater detail.

4.1 Usage scenario

We consider two analysts (Ava and Ben) collaborating to pursue a line of investigation into a large dataset containing 1,700 documents including intelligence reports, news articles, web pages, and pictures to uncover the hidden story (such as the VAST Challenge 2007 scenario [40]). The two analysts use the VisPorter System on two tablets individually, and share a touch-enabled tabletop and one large wall display.

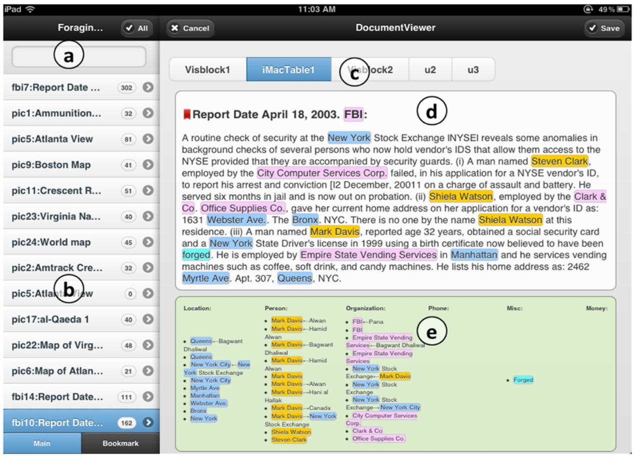

Fig. 2 Foraging tool—Document viewer

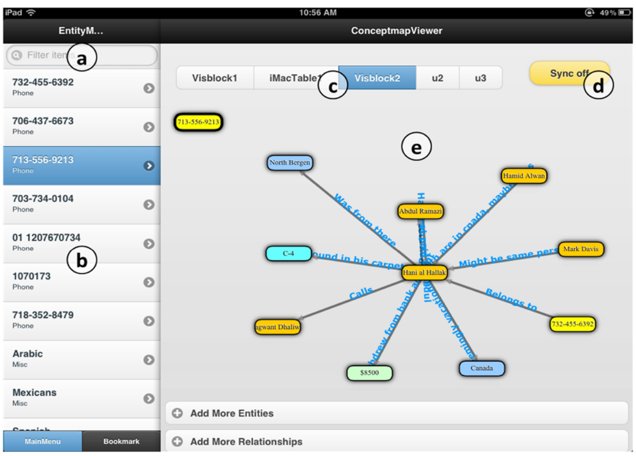

Fig. 3 Foraging tool—ConceptMap viewer

Both analysts start their analyses simultaneously using the Foraging tool on their personal tablets (Figs. 2, 3) independently. They quickly read many documents on the Document viewer (Fig. 2) in order to familiarize themselves with the data and find potential key persons or other keywords that appear repeatedly. Based on these key entities, each analyst performs searches, reads associated documents more carefully (Fig. 2a, d), and scans images. Ava first focuses on the automatically highlighted entities on the Document viewer (Fig. 2d) since she can see the entity type by color, but she finds there are keywords and unknown names that are not identified and highlighted by the system, so she adds them as new entities. If new relationships between specific entities are identified while reading a document, Ava and Ben establish connections between two related entities. For example, Ava adds a relationship between the "Sally" and "Tropical fish" concepts and labels it "is a marketer of." Ava verifies and removes some incorrect relationships between entities for the current document (Fig. 2e). The analysts also begin bookmarking the interesting documents or throwing documents to the large displays or the other user's tablet.

However, as their individual analyses progress, both analysts encounter difficulties in sharing their findings or important insights due to the physical separation of their individual lines of investigation on each tablet and lack of direct awareness of what the other analyst is working on. Thus, they decide to directly share and collect documents, pictures, and concept maps on the wall and tabletop displays. Both analysts flick the documents in the direction of different displays on the Document viewer when they find interesting information or want to reference them later and tap important entities to share the concept map with another analyst (D2). Viewing shared documents on the common space facilitates the direct sharing of interesting pieces of information and discussion about their immediate findings. For instance, while the analysts discuss an epidemic outbreak, Ben wants to know when the outbreak was first noticed. Ava immediately flicks the document related to the time line of the outbreak toward the wall display for Ben to observe (D2).

As the number of documents on the shared display increases, Ben wants to better understand the relationships of the collected documents on each large display. So they start organizing documents spatially on the wall display and tabletop using various central factors, such as locations and timelines (Fig. 4) (D1, D3).

The analysts build the concept maps collaboratively as they continue identifying and making relationships between entities. As the investigation progresses, Ben wants to see a larger concept map which includes more entities, but it is difficult for him to see all related entities on the small screen of the tablet. So he visualizes the larger concept map on the wall display by selecting and tap-holding multiple entities on the ConceptMap viewer to transfer them to the wall display (D2).

They move between two large displays to analyze shared information and to discuss questions about documents organized on different displays (D1, D3). They often refer to their tablets for individual analyses. The spatial organization of documents across displays (D1, D3) facilitates convergence to a common understanding of the results. A common final hypothesis can be successfully reached by two analysts using VisPorter.

4.2 Sensemaking tools

The VisPorter system consists of two main sensemaking tools: the *Foraging tool* (consists of *Document viewer* and *ConceptMap viewer*) and the *Synthesis tool*. Each of these is primarily designed to support different stages of the sensemaking process [35]. These two tools directly match the two sensemaking loops in the Pirolli and Card model:

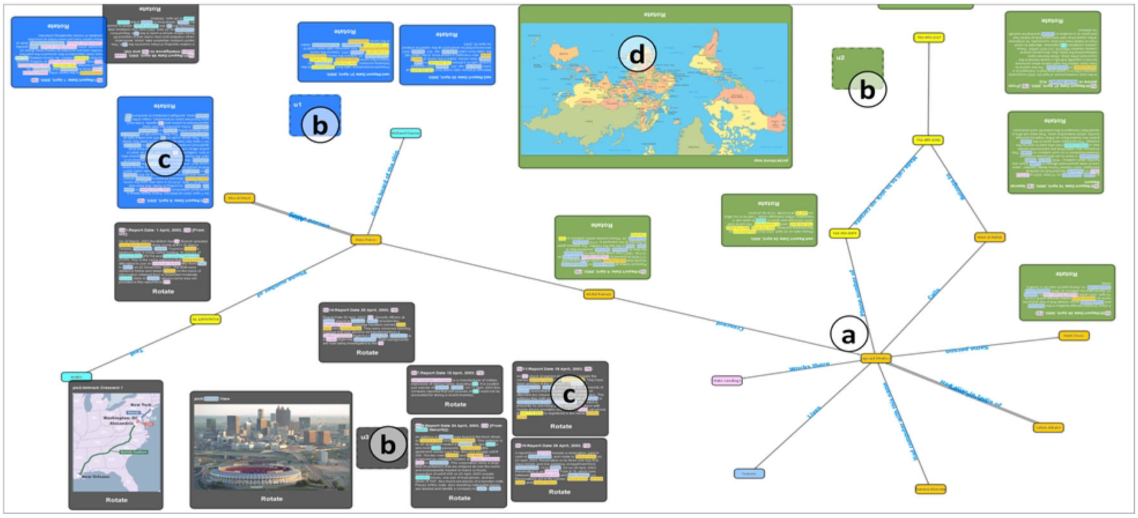

Fig. 4 Synthesis tool on the shared display

Foraging and Sensemaking Loops, respectively. As Vogt et al. [20] show, supporting the division of responsibilities for these two loops showed very good performance in the case of analysis for collaborative sensemaking. One way to achieve this is to support two specialized tools for foraging and sensemaking, which are supported by suitable display affordance (D3). The user interfaces for the Foraging tool (Figs. 2, 3) are designed for personal analysis and devices easily carried by users, such as tablets and smartphones. The Synthesis tool allows users to take advantage of large screens by organizing documents and concept maps spatially on the screen, enabling the integration of various results from multiple users and devices (Fig. 4).

4.2.1 Foraging tool

The Foraging tool involves sorting through data to distinguish what is relevant from the rest of the information. The individual spaces provided by the Foraging tool were inspired by the foraging loops of the sensemaking process. Even though users are collaborating on the analysis, they need to spend a considerable portion of their work searching, filtering, reading, and collecting relevant information individually. This tool is designed to facilitate these individual tasks on personal devices. The tool includes two main viewers—the *Document viewer* and the *ConceptMap viewer*.

The Document viewer focuses primarily on individual content exploration and identification of important entities and their relationships (Fig. 2). Discretized foraging space is useful for a user's sensemaking tasks. Users can read, search, retrieve, and bookmark raw data such as text, images, etc. via a mobile application interface. The viewer allows multiple keyword searches, the creation of entities and relationships and annotation for each document. A search result is ranked and ordered by tf-idf [41] values for the keywords. The viewer includes a document (Fig. 2d) and an entity-relationship list (Fig. 2e). Users can add entity or relationship interfaces and annotation through the similar interfaces used in VizCept [14]. Each document is automatically parsed for entities using the LingPipe library [42] and the extracted entities are highlighted in different colors based on entity type (e.g., people, locations, etc.). At the top of the interface (Fig. 2c), toggle buttons show a list of target devices which can communicate with the device in use; these buttons are dynamically updated based on available displays.

The ConceptMap viewer allows users to visualize entities and relationships in a force-directed layout concept map [43] (Fig. 3). Users can add, select, remove, and search within the created concepts on the entity list panel (Fig. 3b). In the right panel, selected concepts from the entity list panel are visualized in the ConceptMap viewer. A user can drag and drop entities or concepts onto the ConceptMap viewer using touch inputs. Like the Foraging tool, the ConceptMap viewer allows users to create entities and relationships via the collapsible user interface or by simply tapping specific entities (Fig. 5). The viewer has a Sync button (Fig. 3d) that when switched on, directly shows the personal controls and views of individual concept maps on the Synthesis tool of the target large display.

4.2.2 Synthesis tool

The Synthesis tool involves utilizing the information pulled aside during the foraging process to schematize and form a hypothesis during the analysis. This tool emphasizes collaborative synthesizing of the collected information on the shared space while the Foraging tool is concerned more

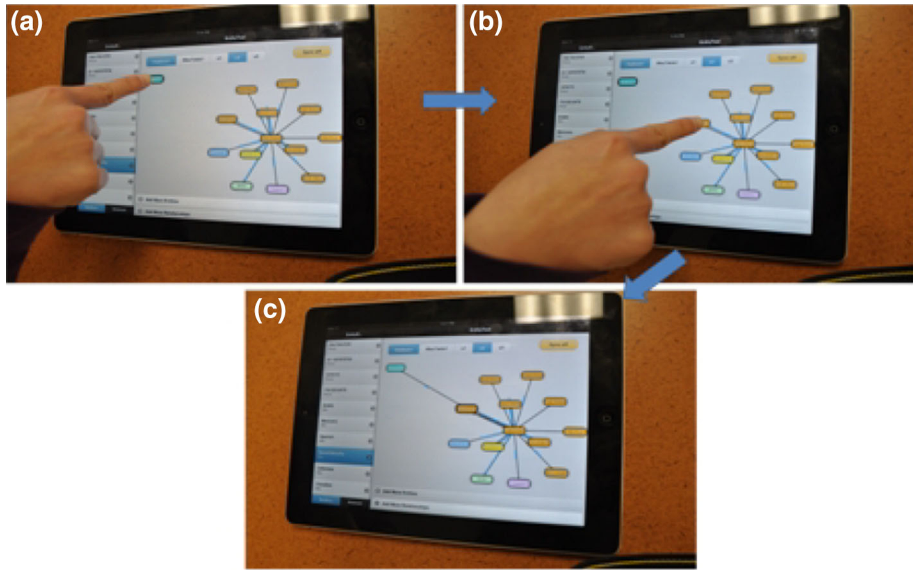

Fig. 5 Easy to connect between two entity nodes by tapping gestures

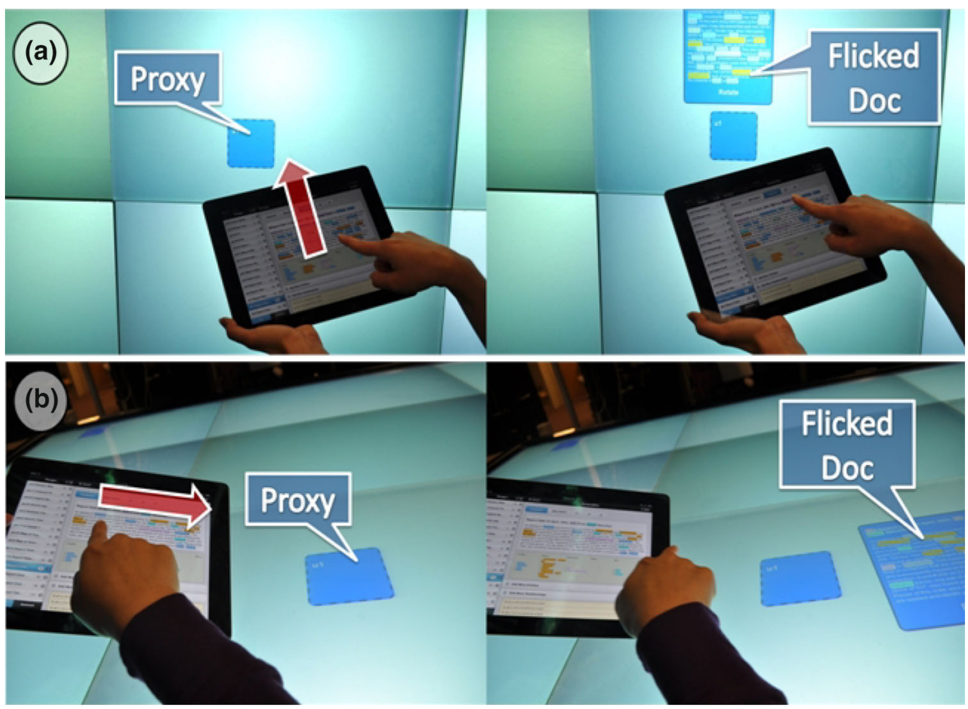

Fig. 6 Swipe and drop the document onto the shared displays: **a** wall displays and **b** tabletop display

with gathering, and verifying information. The Synthesis tool enables the user to integrate findings that have been collected on different devices by dragging and dropping information (e.g., documents, concept maps, entities). Figure 4 shows documents and a concept map (Fig. 4a) created by users. The Synthesis tool facilitates spatial organization of the *information objects*, which can include text documents (Fig. 4c) and images (Fig. 4d) from different users and different devices (D1, D3). As with the Document viewer in the Foraging tool, entities are highlighted in the Synthesis tool.

4.3 Display proxy interface

In the space created by VisPorter, users and portable devices need to move around and above another display and users often need to throw documents from one display to a specific location on a nearby display. So, moving an information object between devices relies on the physical presence of users and devices and their locations. To show other displays' physical locations, VisPorter provides an interface "Display proxy" which allows users to spatially and visually connect to a specific device through the screen space (Figs. 4b, 6). When a new device engages one of the VisPorter tools, all other devices display a visual reference to the associated display proxy on the Synthesis tool. The display proxy provides a spatial reference for the specific display on the other displays. It represents spatial target positions for transferring objects (Fig. 6a, b) as well as the availability/connectivity of different displays.

The proxy is designed to support motion-tracking systems which enable devices to detect when they are in mutual proximity. If the proxy is connected to a motion-tracking system capable of body or object tracking (e.g., VICON, Optitrack, etc.), it is an effective spatial reference for other displays and devices in a given physical space. If motion tracking is not supported, these proxies can be dragged and dropped on the screen space for users to manually determine a drop position.

4.4 Gesture-based interaction

In VisPorter, users can "physically" throw a piece of information to someone who is nearby or to a large screen with the flick or tap of a finger through the use of two different types of VisPorter tools (D2). All information objects including text documents, images, and concept maps are transferred around the location of the display proxy on other large displays. VisPorter employs gesture-based techniques for moving an information object between the Foraging tool and Synthesis tool. When users transfer an information object from the Foraging tool to the Synthesis tool, the position where it is dropped can be determined by one of the four swiping directions (i.e., up, down, left and right) (Fig. 6). For example, if a user swipes toward the right side of her tablet, the flicked document is then dropped on the right side of the associated proxy on a target large display.

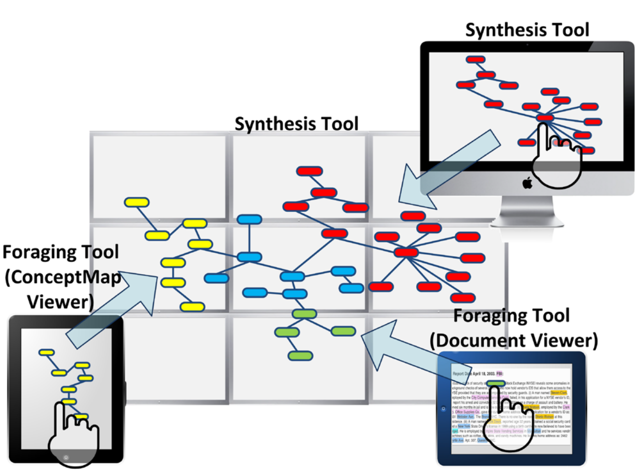

Fig. 7 Transferring and merging individual concept maps and entities in a wall display through tap-holding gestures

The tap-hold gesture is also used to transfer an entity or concept map to the Synthesis tool, and users can merge individual concept maps with the larger concept map on the Synthesis tool through the tap-hold gestures (Fig. 7). For instance, multiple users can create their individual concept maps independently on the personal displays and combine them with a large concept map on the shared display (e.g., wall or tabletop displays). Generally the size of these visual objects on the screen is fairly small, so tapping is a more useful gesture than swiping.

On the other hand, moving documents or entities between two large displays running the Synthesis tool is carried out through display proxies and simple gestural interactions. If a user wants to send a copy of a specific document from the synthesis tool on a tabletop to a wall display, she can simply tap-hold both the document and a device proxy of the target device at the same time.

4.5 Software architecture

To support interoperability and spatial interawareness (D4) among different types of devices, we employed web architecture for VisPorter, which consists of multiple web clients and a server. This architecture is based on bidirectional communications among multiple devices and applications via Websocket [44], which enables a persistent socket connection through a server. In our infrastructure, the data between the client and server are exchanged in compressed Javascript object notation (JSON) format [45].

To ensure support for interoperability, an important issue is how the information produced by different displays is distributed and synchronized. The clients provide user interfaces and visualization views in which information objects and concept maps are displayed. All clients, such as the Foraging tools and Synthesis tool, are independent web applications which share application state information, input events, data queries, etc. with other clients through the server. All communications among the devices (clients) are mediated by the server. For example, when a gesture event (i.e., flicking a document) occurs on a client on a tablet, an associated message comprised of gesture types, information queries, target device id, user id, and document id in JSON is sent to the server. The server then processes the JSON message by retrieving a flicked document from the database and returning requested documents to another client on a target device. The server also keeps track of device configurations and the status of applications in order to manage distributed software and hardware resources in VisPorter. To manage the location information of each handheld device from a motion tracker system, VisPorter system maintains an independent input server which transmits each device's location information to the server.

VisPorter clients (i.e., the Foraging and Synthesis tools) are implemented with Javascript, HTML5, CSS, and JQuery (for the foraging and entity tool) and the servers are implemented with Node.js [46]. To use the touch interfaces on the wall and tabletop displays, we used TUIO [47]. The concept map is developed with HTML5 Canvas. Since the information objects are based on a form of DOM elements, users can wrap various common data types (such as text, images, and videos) and various web services in the DOM elements.

5 Evaluation

We conducted an exploratory study of our VisPorter system using various types of touch-enabled displays. We had two main goals. The first goal was to better understand how the multi-display environment created by VisPorter impacts the users' processes of co-located collaborative text analytics. Specifically, we wanted to examine how users externalize their syntheses into the physical space provided by the multi-display environment to extend previous findings that were limited to single large displays [34]. The second was to evaluate how well the design (D1–D4) appropriately supports the sensemaking tasks in collaboratively solving complex problems with our tools and multiple displays.

5.1 Participants

We recruited 24 participants, 4 female and 20 male. We selected participants from a pool of computer science graduate students. Our sample reflects the male to female ratio in the computer science department from which the participants were recruited. All participants are required to have prior experience with visual analytics or information visualization by having taken a course on either topic. Their ages ranged from 20 to 39. A pre-session survey confirmed that none of the participants reported familiarity with the use of large displays or tabletop displays. While the subjects were not actual analysts, they had basic knowledge about how to approach analytic problems from their required graduate level classes. Prior user studies in collaborative visual analytics have also made use of participants without formal training as data analysts [20, 22]. The participants were grouped into 8 teams with three members each (G1–G8). Four teams included members who knew each other beforehand, but the other four teams did not.

5.2 Task

In this study, users performed an intelligence analysis task, in which they analyzed a collection of intelligence reports to identify potential illegal human activity and motivation. Each team conducted the analysis in a co-located synchronous fashion using VisPorter in a multi-display environment. The task was to identify the latent plot hidden within a fictional intelligence report dataset [48]. The dataset consists of 41 documents as well as 25 pictures and includes three subplots that compose the main terrorist plot. The dataset is relatively short and an appropriate size to complete within the 1-h time limit, as in prior work [20, 38]. It includes considerable "noise," which may lead users to unrelated hypotheses. The tasks were common enough such that they did not require any specialized knowledge.

Participants were to use VisPorter to forage information from the dataset that most efficiently leads to productive hypotheses, and then to synthesize information from multiple intelligence reports. Their goal was to provide a hypothesis solution with supporting evidence including details such as who, what, where, when, and how they are connected.

Before starting the analysis, all teams were given an answer sheet to complete during their analysis. This answer sheet asked the teams to provide their answers to four questions based on [49], including the entire situation and plot, key persons, the time frame of the plot, and the important locations of the plot, in the short answer format. The short answers were graded by an author, as shown in Table 1. The grader awarded each correct answer 1 point. The maximum possible score was 10 points.

5.3 Apparatus

A suite of devices comprised of *iPads* (one for each participant), a touch-enabled *iMac* (screen tilts to allow for tabletop or vertical use), a shared wall display and a tabletop display were made available to the participant teams during the study. These displays provide very different device affordances. The eight teams had access to all devices at all times during the analysis and the participants were free to choose devices based on their needs. Both the tabletop and wall display consist of nine tiled back projection displays arranged as a large 4ft by 6ft (3,840 × 2,160, 82.5 in. diagonal) horizontal or vertical surface screen with a PQ Labs' 32-points Multi-touch overlay.

5.4 Procedure

The study was carried out with each of the 8 teams conducting a 1- to 1.5-h-long analysis session in a laboratory environment. All three team members met in the lab at a scheduled time. A demographics questionnaire was administered to each participant and then they were trained together on how to use the system for 20 min. The experimenter first gave a brief demonstration and

Table 1 Study results

	G1	G2	G3	G4	G5	G6	G7	G8
Primary style	FS	SD	FS	FS	SD	FS	SI	SD
Secondary style	No	FS	No	SD	No	SD	SD	FS
Cross device organization styles	None	Single entity (location)	None	None	Single entity (location)	Multiple entities (geography/ organization/ people)	Single entity (location)	Multiple entities (telephone + money/ location + event/ people)
Score (out of 10)	2	6	3	7	4	6	4.5	8
Number of flicked documents (iPads to large displays)	11	21	22	43	16	67	50	35
Number of flicked entities (iPads to large displays)	12	20	5	37	32	1	0	102
Number of large displays used	1 Tabletop	2 Tabletop and wall	1 Tabletop	2 Tabletop and iMac	2 Tabletop and wall	3	3	3
Objectification behaviors	No	Yes	No	No	No	Yes	No	Yes
Knew each other before the study	Yes	Yes	No	Yes	No	Yes	No	No

introduction to the two main tools of VisPorter and he also introduced the set of available displays and devices. During this training session, users could freely test each feature of the system on the different displays. However, no analytic approaches or strategies were discussed during the training session to avoid influencing the participants on their analytic tasks.

After the tutorial session, all participants started a 1-h analysis task sitting or standing in front of the large displays. The dataset was pre-loaded before the study and the questions are also given. The Foraging tool was activated on the iPads and the Synthesis tool was started on the wall, tabletop, and iMac displays. During the analysis, participants were allowed to ask the experimenter how to use VisPorter.

After 1–1.5 h of the analysis session, a debriefing followed the analytic session and participants were allowed to access their analysis results on the displays. Each team was then asked to complete an answer sheet and a post-questionnaire concerning their findings and their user experiences as they completed the analysis task with the system. A semi-structured group interview was conducted at the end of the session involving all team members.

5.5 Data collection and analysis

All sessions were video-recorded and observation notes were taken by a researcher who remained in the experiment room. Screen activity was recorded for all work done using the Synthesis tool on the wall, tabletop, and iMac displays; screenshots were taken at 30-s intervals. All concepts, relationships, and notes created by the teams were logged in a database and retained. Additionally, all interview results and conversations during the collaborative analysis sessions were audio-recorded and transcribed by the authors. Our analysis was mostly qualitative in nature. We analyzed the data using a grounded theory approach. An open coding session was first performed on our collated observation notes, interview transcripts and post-questionnaire results to uncover high-level themes, for example, the participants' use of the various devices and their strategies for sensemaking and collaboration. The authors discussed these issues, and collated them on the whiteboard. Based on this information, we defined a set of high-level themes regarding the sensemaking process.

We then implemented a second round of more detailed coding using the high-level themes as categories. After important analytic strategies were derived, we consolidated our findings by conducting a validation procedure of those strategies by examining other types of relevant data including video and audio recordings of the sessions. In this paper, we present the common strategies with supporting details from different sources wherever appropriate.

6 Findings

The key activity in the use of the VisPorter, which we elucidated from our study, is summarized in Table 1. The table shows how many groups fell into each collaboration style, how much each team exchanged or transferred information across different devices, scores based on the identified plots, etc. We do not focus on statistical analysis of results. Instead, we are more interested in how the process of sensemaking is influenced by using VisPorter. As Huang et al. [2] emphasized in their display ecology study, our evaluation focuses on how the display ecology, created by VisPorter, supports collaborative text analytic tasks, rather than measuring the use of VisPorter's features and displays. Each finding will relate to qualitative results and discussions described in the subsections. In our study, we observed four common strategies which the participants used during collaborative sensemaking with VisPorter.

6.1 Collaboration styles with multiple displays

We first focused on understanding how teams worked together and coordinated their analysis tasks across the different displays. From our observations, the participant teams had varied work division approaches, but their approaches can be generalized into three types (Fig. 8).

Strictly individualized (SI). For this case, each participant had strong ownership of a specific large display in the environment (Fig. 8 left). The tabletop, wall, and iMac displays were divided among the three team members and were used as individual workspaces in addition to the individual iPads. In this approach, the teams assigned portions of the initial information to the team members and each team member focused on individual analysis on a different large display. Members occasionally looked at the other members' displays, but there was almost no discussion or other significant collaboration among the participants during the analytic session. Therefore, until the debriefing session, these participants did not combine and synthesize individual findings from each display. All users commented they wanted to concentrate on their individual analysis. The one team that employed this approach reported low scores on the "enjoyment of system use" question on the post-session survey (see Sect. 6.5).

Semi-divided (SD). Like the "strictly individualized" case, each participant had ownership of a specific large display and concentrated on working on that display (Fig. 8 right). The team members divided the given data between the shared displays. Each member mainly worked with his or her large display. However, during the session, they looked at each display together, and shared the knowledge/insight gained from the data as needed. They often shared the findings with each other and asked the other team members to come closer to the display for assistance. Once a member found possibly useful and interesting information for another participant, he/she approached that user's display and flicked the document. However, each member still focused on an individual analysis with one display.

Fully shared (FS). In this case, participants did not have specific ownership of any large display (Fig. 8, middle). If the team used multiple large displays (G4, G6), they first discussed the categories of data and assigned each to a suitable large display based on the contents and entities. In contrast to "semi-divided," all users spent a fair amount of time analyzing data around the tabletop display instead of each member working on a specific topic with separate displays. They shared all information with each other and collaborated to reach the goal. When they needed to organize or forage information on different displays, they immediately moved to that particular display or transferred related information from their iPads or tabletop to the corresponding displays.

Table 1 shows which collaboration styles each team used most often, and the second row shows other styles that they used sometimes. Four of the eight teams (50 %) primarily used "Fully shared". The "Fully shared" model was used the most among the teams, while the "Strictly individualized" approach was used least. We observed that G2, G4, G6, G7, and G8 changed to secondary styles as necessary.

6.2 Cross-device organization strategies

An important research question in our study concerns how users spatially organize and distribute their data and findings on multiple displays (D3). The discretized space supported by VisPorter allows users to arrange documents and entities onto different displays. We examined how analysts leverage such discretized screen space of multiple displays to augment the information with synthesized meaning. The displays enabled the participants to spatially organize hypotheses and evidence, providing external

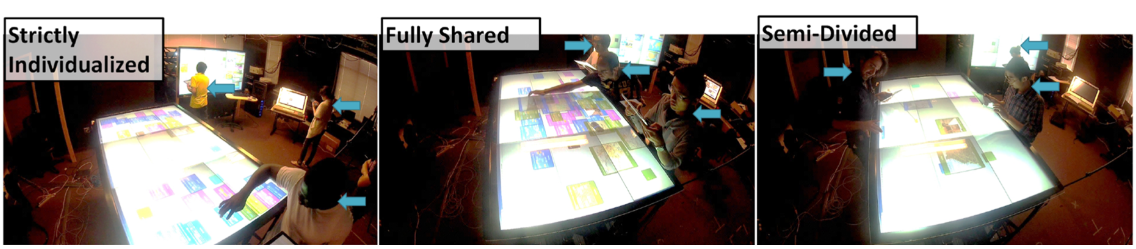

Fig. 8 Three collaboration styles for multiple displays. *Blue arrows* indicate users (color figure online)

representations and spatial insight (D1). These activities can be classified with the evidence marshaling and schematizing stages in Pirolli and Card's sensemaking model [35].

We observed a variety of spatial organization methods performed by the participants during their analysis using VisPorter. Spatial organization strategies of documents on each single large display echo results of previous studies on large displays [34]. For instance, the participants created spatial structures such as document clustering and ordering on the display. We also observed "incremental formalism" [50]. The teams that used SD and FS styles incrementally morphed their organization of data across displays into more accurate arrangements as their analysis progressed. In this section, we focus on salient organizational strategies used with multiple large displays. The multiple display types allowed the participants to organize the data based on the device capabilities and visualization need. We observed two categories of cross-device spatial organization.

Single entity types: Three of the eight teams preferred to collect information based on the geographical area of interest. This is because the dataset includes a large amount of location information. Thus, the teams organized data according to a single entity type, *location*. For instance, when G7 decided to organize the given data into three primary areas of interest (Virginia, NY, and Boston) based on the location; each area was then mapped to a particular display; Virginia data to the wall display, New York data to the tabletop, and Boston data to the *iMac*. Since there were many documents related to Virginia that included locational data, they decided to use the large wall display for that data.

Multiple types of entities and visual representations: Two teams focused more on arranging data in different displays, based on multiple entity types. G6 organized information by different entity types such as places, organizations, people, and events in each large display. G8 also distributed data to three different displays based on (1) *telephone numbers and money*, (2) *locations and events*, and (3) *people*. This strategy allowed the team to use different visual representations on different displays based on the type of information being visualized. For instance, G8 formed hypotheses on three displays (Fig. 9), based on an event timeline (iMac), people's locations and trip routes (wall), and telephone and bank accounts (tabletop). On the tabletop, a concept map was presented to determine how people are related to each other, based on telephone numbers and bank accounts. Tracking the telephone number and money, required seeing the relationships among people. On the wall display, the team opened a large map and overlapped related documents for the locations of different bomb plots and explosives. On the iMac, participants spatially organized a time sequence (horizontally) with the future travelling movement of the key people. By integrating with the location of explosives, they deduced the possible target locations.

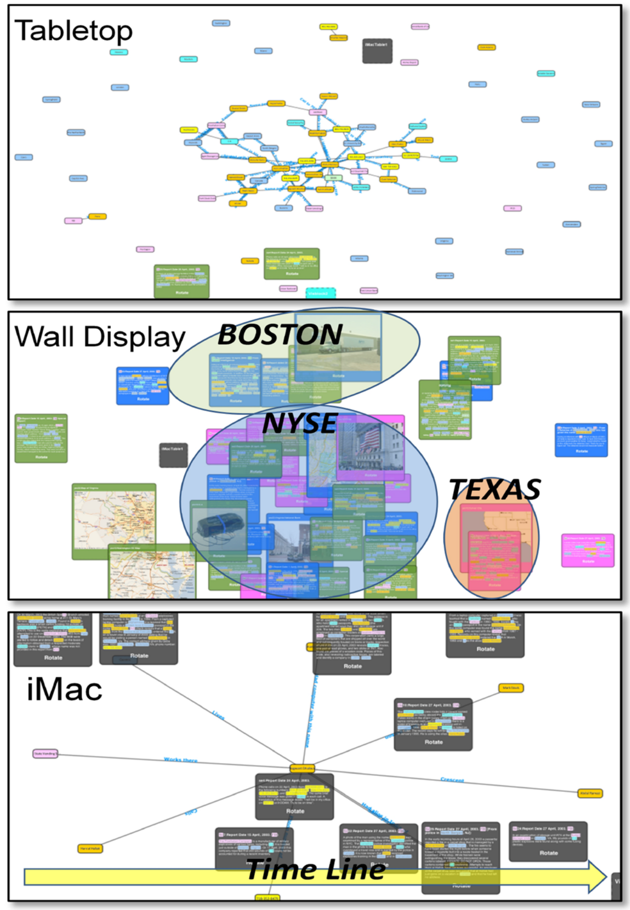

Fig. 9 Organizing information based on multiple entity types on different displays. On the figure of the wall display, we added labels pertaining to participant explained regions of clustered documents described to us during the debriefing

6.3 On-demand extension of display space

We analyzed when participants "throw" information to another device and the rationale for why they transferred their activities to the chosen device. All participants were asked what information and why they transferred from their personal tablet to the other displays in the post-interview.

Offloading Information. We found there were two types of offloading: *self-referencing* and *team-referencing*. Most of the participants flicked documents, images, and entities from the private space of their own iPad to the shared screen space, but did not immediately use them in their thought process. Instead, the participant merely used the spatial affordance of the tabletop to store information for later exploration or bookmark potentially important documents. Many participants mentioned that they employed the tabletop only for self-referencing. For example, participants often transferred documents to the tabletop when the document included keywords or entities that were hard to remember, such as exotic names and phone numbers, in order to reference them later when they came across the entities in different documents. Interestingly, all participants used this approach to record important information instead of using the bookmark feature in the Foraging tool. On average, participants bookmarked only 1.8 documents ($\sigma = 2.31$, median = 1).

Flicking documents for the purpose of offloading allowed for opportunistic collaboration. Even though participants flicked documents for individual use, the shared (public) documents led to unexpected collaboration opportunities. For instance, during the discussion, one participant flicked a relevant document (for self-referencing) on a tabletop, and thereafter slid that same document directly to another participant who needed it during collaboration.

Of course, there were teams who frequently flicked documents for the purpose of active collaboration or "team-referencing." In such teams, each team member was well acquainted with what other members were working on and if they found possible interesting information for another member while they were reading a document, they flicked the document onto the tabletop or another shared display. While this behavior directed their individual and collaborative investigations, it occurred at the cost of polluting the shared display workspace with multiple documents and entities.

Our observations concerning the main use of the shared displays in multiple display environments as a form of external memory resonate with observations concerning sensemaking on single large displays [34].

Need for Larger Space. Another notable observation in favor of multiple displays is the support for on-demand increase in screen space as needed for analytic activities. While foraging for information contained on the iPad, participants often required a larger concept map or needed to open multiple documents simultaneously. On the iPad, the application takes up the whole screen; this was perceived as beneficial to direct attention, focus, and thinking [39]. However, the inability of the device to support viewing larger concept maps and multiple documents simultaneously was a key barrier to the use of the device for visualization or analytics-related purposes. One user commented:

> "*I could access only one document at a time with an iPad, but I often wanted to check more than two documents at the same time. Also, I needed to see relationships between entities across different documents but couldn't read multiple documents on an iPad. In response, I spread multiple documents on the tabletop by moving them from my iPad.*"

The participants could extend their workspace physically by flicking his or her content or entity from the personal tablet screen to the tabletop. This lightweight gesture interaction allowed participants to use nearby displays as extensions of their personal displays. No one attempted to reverse this gesture and flick information from the large display to an iPad.

Participants strongly agreed that VisPorter's gestural interaction to move objects was extremely useful and allowed them to take advantage of nearby screens to transfer tasks; (4.6/5.0, $\sigma = 0.67$, median = 5). Almost all participants flicked the contents of their personal display onto a nearby larger screen in order to explore multiple documents or visualize on a tabletop capable of displaying more detail than is possible on an iPad.

6.4 Objectification of information

Objectification of information [39] occurs when users appropriate a physical object as a "carrier" of a specific thought or concept to be shared in a direct, transparent, and quick manner, solely focusing attention on the material being handled (e.g., the concept) as opposed to undertaking procedures to share information divorced from the meaning of the object itself. In our case, objectification refers to how participants assigned meaning to devices. They associated concepts to particular devices, and used these "physical carriers" to expand their thinking.

We found that after organizing many documents that were related to a specific entity on a single display such as the iMac, this display was then regarded as a physical entity or representational proxy when team members discussed that topic. For instance, after collecting or moving all documents related to a suspicious person in the dataset onto the iMac, participants frequently pointed to and referred to the iMac as the suspicious person when discussing relationships among events involving the person. Three teams (G2, G6, G8) displayed these interesting behaviors. This type of physical referencing facilitates efficient communication among people [51]. In the interview session, one user commented on this facilitation.

> "*After collecting many related documents in iMac, I found that one guy was involved in several issues and events. Just calling him didn't seem sufficient when we discussed him. I felt like that the large quantity of information related to that guy and iMac becomes a physical icon. When I need to discuss something relevant to him, it seems easier and more natural to map or point to that iMac.*"

6.5 User feedback

In our post-session survey, VisPorter was very positively rated for finding hidden hypotheses in the dataset (Fig. 10). The question "Rate your enjoyment when using the system?" rated an average rating of 4.0/5.0, with $\sigma = 0.85$. The question "How useful was the system in finding answers?" rated an average rating of 3.6/5.0, with $\sigma = 1.16$. On the other hand, for the question "How much did the system lengthen time required to analyze the data?" received an average rating of 1.9/5.0, with $\sigma = 0.79$.

In the interviews, the majority of the participants gave mostly positive feedback about the physicality and spatiality of VisPorter on multiple displays.

> "*I liked the idea of using my iPad to analyze each section of a document and then dragging it to the large display to organize information spatially*."

> "*The key advantage of this tool is that I am able to physically retrieve the information based on its place on the screen*."

> "*It was beneficial to be able to lay out data in multiple large displays. It also made working with a team faster, since we weren't all looking in one place*."

On the other hand, a few of participants felt stress using multiple displays due to the lack of information management features across multiple displays.

> "*Many large displays are distracting and it is difficult to find specific information if too many documents are displayed*."

> "*I feel very insecure, because I was always afraid that the information on the screen would disappear. It's easy to store information when you write it down. Then, when you want to retrieve the information, just get the paper. However, with multiple screens, we can't easily record the information*."

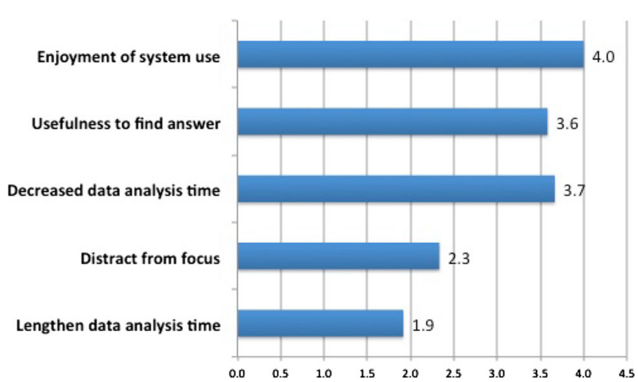

Fig. 10 User feedback in the post-session survey (0–5 scale)

7 Discussion

7.1 Impact of VisPorter on the analytic activities

7.1.1 Performance factors

After the 1–1.5-h analyses, six of the eight teams successfully discovered the overall situation, and seven teams successfully determined the key player in the dataset. However, from the results of our study (see Table 1), we identified different collaboration styles and factors affecting the performance of the teams.

Specifically, we found G1 exhibited very low performance due to lack of information sharing and awareness of the other users' analyses. While G1 used FS and all of the team members shared a single tabletop, they neither shared their findings actively on a shared display nor tried to connect pieces of information different members had found. G1's members concentrated on individual analyses using a tabletop and each team member had different hypotheses than the other team members. As a result, G1 provided considerable misidentified information, yielding the lowest score among the teams.

Also, it is worth noting that the amount of exchanged (transferred) information between displays also appears to influence performance. The total number of documents transferred by each team ranged from 11 to 67 and the number of entities, ranging from 0 to 102 entities, makes a difference. We observed that a group who shared and transferred more information across displays seemed to produce better results. Comparing groups that have the lowest and highest scores, we can see the groups that received the high scores (G4, G8) exchanged a larger number of documents and entities between their individual devices and the shared large displays. They also employed more displays than the teams that received the lowest scores (G1, G3).

We also examined how objectification behaviors might affect their scores with multiple displays. However, the small sample size did not allow us to identify any significant correlation between the scores and this interesting behavior.

7.1.2 Spatial and physical actions

VisPorter enables people to distribute knowledge and ideas around the physical space. Spatial organization of collected information on displays was very fluid on VisPorter with multiple displays (D1). Also, the lightweight gesture-based techniques used to move objects between devices supported by D2 make it possible for users to perform all of the cross-device activities observed in the study. Throughout analysis sessions with VisPorter, participants

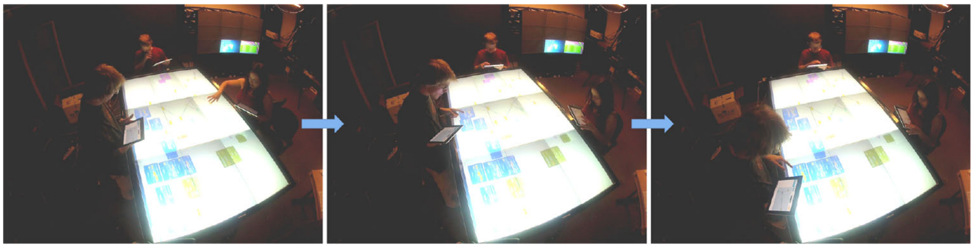

Fig. 11 Cross-device referencing with physical navigation. The user in G4 analyzed the concept map on his iPad and text documents on the tabletop. He used physical navigation to scan the documents on the tabletop rather than use the search feature

used physical navigation extensively to forage documents on the displays (Fig. 11). For instance, participants frequently re-found documents by physically navigating the multiple display space. One participant mentioned that such experience with foraging documents in VisPorter was very similar to finding information from piles of papers on different desks. In many cases, users did not even use the keyword search feature, but tried to find items through physical navigation. During the post-session interview, users commented that because documents were already spatially organized across the displays, they could rapidly re-find the spatial location of the reports on the different screens using spatial relations. One participant stated:

> "*I could not remember how to spell specific keywords when attempting to re-find documents, but I could remember where the information had been placed.*"

7.1.3 Opportunistic activities

VisPorter extends the analytic workspace opportunistically, enabling additional externalization and organization of information as necessary. Opportunistic activities were enabled because the participants did not need to focus on memorizing the data, only flicking and organizing it (D2 and D3). They naturally off-loaded information using the tools at hand. We observed that the appropriation of personal and shared spaces was improvised according to the participants' needs. As shown in offloading information activities to large displays, based on user's needs and preferences, the role of each display and the user's activities continually underwent transformations among different displays during the analysis sessions as needed. As mentioned, the tabletop was generally recognized as a public space, but participants also used it as an extension of their personal displays to see multiple documents and large concept maps.

7.1.4 Promoting the objectification of information

Many current collaborative sensemaking tools based on single displays (e.g., [14]) embody a model of collaborative sensemaking whereby users perform collaborative work with a shared focus and simultaneous individual control of visualizations on separate single displays. In these tools, the collaborative sensemaking is for the most part confined to the single shared virtual space. Conversely, VisPorter allows users to collaborate using interconnected devices that separate individual and shared work with natural physical affordances. This enables people to distribute knowledge and ideas around the physical space where the displays take on meaning, as an example of distributed cognition [52] in action. This characteristic of VisPorter promotes the objectification of information, which enables regarding concepts through physical devices as efficient representational proxies. The device becomes the information. Objectifying all the information related to the suspicious character as a physical display allowed them to consolidate all of the attributes of that character as a single unit, and physically reference that unit, while deliberating the character's role on the plot.

This form of objectification is distinct from the notions of *object-orientation* [1] in that the object represented is conceptual in nature (e.g., the suspiciousness of the person) and the representation itself is a physical device, not just a visual representation on a display.

7.2 Limitations and future work

Our study and the system features presented have several limitations. A real-life intelligence analysis scenario is highly unpredictable, and sometimes has no specific solutions. Analysts encounter, carry, and consult various pieces of information at opportunistic moments, transitioning between spaces throughout the day and week, as needed. And the size of the information and data for such a scenario has no limit. Therefore, a longitudinal study may be more appropriate to better understand such characteristics of sensemaking. However, in our study, a clear goal was given to the participants within the lab analysis setting. The dataset is composed of a small number of documents in contrast to the amount of data used in genuine intelligence analysis scenarios. These issues may reduce the ecological validity of the studies somewhat, but we chose the feasible analysis task and size of dataset enabling users to complete their analytic tasks within one and a half hours. We suspect that in a longitudinal setting, the benefits of display ecologies will become even more valuable.

In our data analysis, the social relationships in sensemaking are minimally considered. Whether or not the participants know or trust each other implicitly may affect the collaboration styles and performance significantly. Table 1 shows whether the participants knew each other beforehand, but it would be interesting to see whether there is any correlation between collaboration styles with multiple displays and such social issues.

In a study about sensemaking and multi-display usage, it can be difficult to appropriately attribute actions to motives. For example, the document flicking actions potentially embed many different meanings based on users' intentions (e.g., offloading, self or team referencing, or simple transfer between displays), which cannot always be accurately judged by the activities themselves. Thus, we depended on the interviews and quotes to identify those patterns. In the future, we can use "think aloud protocol" to ask the participants about their intentions when they are flicking documents.

Finally, VisPorter lacks support for provenance, which might hamper the analysts' full use of the space. One participant mentioned that he was worried that he might lose his information when multiple collaborating users are moving the information around in the space. The tool provides a very high degree of freedom in spatially organizing and distributing information across different devices and displays. Thus, it was challenging for users to keep track of changes made. Provenance information can help users understand how their analytic steps from multiple devices derived a final hypothesis, like IdeaVis's Facilitator display which provides information relating to the work process and history for collaborative sketching sessions [53].

8 Conclusion

In this paper, we presented VisPorter, an integrated multi-device system with intuitive gesture interaction for information sharing and spatial organization. It strives to deliver a seamless experience for collaborative sensemaking across varied devices. The system embodies the idea that the multiple devices should operate as an ecology of mobile devices, desktops, and large displays for organizing and analyzing information. In this ecology, each device is afforded different analysis tasks (e.g., personal displays for foraging and large displays for synthesis), and has different effects on how participants make sense of information. We proposed a set of design principles derived from prior studies of single and multiple display systems. Our study of VisPorter, based on these design principles, with participant teams showed that the concepts of "space to think" [34] extend usefully to multiple display environments that support:

- **Flexible work division:** VisPorter supports flexible work division approaches by allowing team members to coordinate different analytical tasks among physically separated displays.
- **Cross-device data organization:** VisPorter allows team members to organize documents and concept maps onto different displays, based on the device capabilities and visualization needs as well as different entity types.
- **On-demand extension of display space for offloading and sharing information:** VisPorter enables users to move all information objects including text documents, images, and concept maps throughout displays in the workspace by lightweight gesture interactions. These approaches allow users to extend their workspace as necessary and externalize their cognitive processes by transferring individual information or concept maps from a personal tablet to nearby available large displays.
- **Facilitation of objectification of information:** The ecological model of VisPorter presents the greater opportunity for "objectifying" information using the natural physicality and spatiality that the ecology affords.

Based on our analysis of participants' use of VisPorter, we validated the set of design principles for multi-device systems that attempt to provide a cohesive and integrated experience for users. The results of our study inform the design of new sensemaking tools to help people leverage space in ubiquitous display scenarios. Our future research goal is to improve the robustness and usability of the system, and to study the effects of using such a system empirically with a greater longitudinal basis.

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