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Exploring spatially-aware cross-device interaction techniques for mobile collaborative sensemaking

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Abstract

The collaborative decision-making process is traditionally supported by multi-user interfaces, such as large multi-touch screens or interactive tabletops for accessing, relating and comparing different data sources. Since such multi-user interfaces are typically expensive and unavailable outside dedicated environments (e.g. labs, smart rooms), recent works have proposed "bring your own device" approaches that allow users to join their mobile devices (e.g. smartphones, tablets) in an ad-hoc manner to temporarily create multi-user cross-device systems. Such approaches can be enabled by spatially-aware cross-device interactions that have only been explored for simple operations. We conducted a three-step research study involving a total number of 65 users in 18 groups, in order to propose a composition paradigm that offers three interaction techniques for performing more complex operations, such as forwarding to multiple devices queries or query results or aggregating and visualizing search results across device boundaries.

"Keywords: Spatially-aware Devices, Interaction Paradigm, User studies."

1. Introduction and Motivation

For more than two decades, cross-device systems have been envisioned to support people during co-located collaborative group work [Biehl and Bailey 2004; Weiser 1991]; most of them involve different types of devices and often include large interactive displays. Since such multi-user systems are typically expensive and unavailable outside dedicated environments (e.g., labs, smart rooms), recent works have proposed "bring your own device" approaches that enable users temporarily create multi-user cross-device systems by joining their mobile devices (e.g., smartphones, tablets) in an ad-hoc manner [Ardito et al. 2015; Hamilton and Wigdor 2014; Lucero et al. 2011; Marquardt et al. 2012; Rädle et al. 2014; Rädle et al. 2015]. Designs for mobile cross-device interactions have been already proposed, but they mostly support simple tasks, such as file transfer (e.g., photos, videos, contacts) across devices [Chen et al. 2013; Hamilton and Wigdor 2014; Hinckley 2003b; Lucero et al. 2011; Lucero et al. 2010; Rädle et al. 2015; Yang and Wigdor 2014].

With respect to such works, we aim to support complex information seeking and sensemaking tasks that require, by multiple group members, the combination of data from different sources (e.g., websites or apps displayed on different mobile devices). In the most general sense, sensemaking is defined as behaviour, both internal (i.e. cognitive) and external (i.e. procedural), which allows the individual to construct and design his/her movement through time-space [Dervin 1983]. More specifically, sensemaking is the ability or attempt to make sense of an ambiguous situation; it is the process of creating, in conditions of high complexity or uncertainty, situational awareness and understanding in order to facilitate taking decisions.

Let us consider the following scenario exemplifying a sensemaking activity involving complex information seeking tasks carried out with the help of technology. A group of friends, Sherlock, John and Mycroft, meet to plan a one-month summer holiday in London. They sit around a desk and start discussing the property they have to rent. According to Sherlock, it should be close to downtown where all the main attractions are located. John wants a property close to metro or bus stations for a convenient commuting. Finally, Mycroft would like an accommodation in a non-polluted area. Thus, the three friends seek for information on their own personal device, i.e. their tablets and smartphones. Sherlock opens Zoopla[*] Website on his tablet to retrieve properties in central districts of London. In the meantime, John looks at the search results visualized on Sherlock's tablet and types in the TFL[†] Website search box the names of the streets where the properties are located, thus visualizing on TFL map all the metro/bus stations around that streets. At the same time, Mycroft uses his smartphone for retrieving information about pollution by typing, in a specific website, the address of the properties retrieved on Sherlock's tablet. The discussion goes on until they find the property that satisfies all their needs.

Mobile devices, their operating systems and apps are not designed to support collaborative sensemaking activities, as those depicted in the above scenario: people in co-located groups are forced to tedious, time-consuming and error-prone verbal or written exchange of information about performed queries and retrieved results [Hamilton and Wigdor 2014]. Mashup tools, i.e., data-centric applications that allow users to compose heterogeneous resources, thus creating a new web application to perform data exploration activities that exceed one-time interactions [Aghaee et al. 2012; Daniel and Matera 2014; Desolda et al. 2015; Namoun et al. 2010], can be helpful in sensemaking scenario. However, such tools are not conceived for tasks performed by co-located groups of people, but single users [Aghaee and Pautasso 2014; Cappiello et al. 2011; Desolda et al. 2015] or users that collaborate remotely [Ardito et al. 2014a; Jung 2012]. Mashup tools still offer little or no support to combining data or Web search results from multiple devices.

In order to exploit mobile devices working across device boundaries, spatially-aware cross-device interactions have proven to be more usable and less demanding than spatially-agnostic approaches. By exploiting space, users can bring down to workable time and memory demand of executed tasks thus increasing reliability and number of jobs handled at once [Kirsh 1995]. Until now spatially-aware cross-device interactions have only been explored for comparably simple operations, such as object movement across devices or stitching displays, and not for more complex operations, such as forwarding queries or query results to multiple devices or aggregating and visualizing search results across device boundaries.

The main goal of our research is *identifying a data composition paradigm for supporting real and useful sensemaking collaborative tasks*, based on spatial-aware cross-device techniques, i.e., touch gestures and physical arrangement of devices on a desk. This article proposes a set of spatial-aware cross-device techniques that allow users to formulate their queries and reconfigure the data flow between different mobile devices by rearranging them on the physical space of a desk and performing cross-device touch gestures on their display. The design proposals consider the desk as a *physical workspace* where data sources are materialized in space by mobile devices displaying them. Data sources can be *flexibly* combined by moving them around on the desk or by performing touch gestures to quickly express the *situational* information needs of the group. In the studies reported in this article, the design proposals have been enabled by HuddleLamp [Rädle et al. 2014], a tool for tracking devices on a table and making them aware of the locations of all the others. HuddleLamp features, as well as its strengths/weaknesses in relation to other similar technologies, are described in Section 5.

1.1. Contributions

This work falls into two research areas: mashup and cross-device interaction. From the mashup perspective, it proposes a solution to support the co-located collaborative creation of mashup. From the cross-device interaction perspective, it presents composition techniques to combine spatial-aware mobile devices to foster sensemaking activities. Indeed, this work advances the state-of-the-art by proposing cross-device interaction techniques enabled by touch gestures and arrangement of mobile devices on a desk to compose mobile device data sources. The contributions of this article, therefore, concern the following issues:

- *Data Composition paradigm.* With the help of users involved in an elicitation study, we identified the mental model of end users performing data composition operations by using spatial-aware cross-device techniques with their mobile devices.
- *A set of spatial-aware cross-device techniques for sensemaking tasks.* Starting from the results of the elicitation study, we designed, implemented and evaluated three novel spatial-aware cross-device techniques to combine mobile device

* Zoopla is one of the leading website to rent and sell properties in UK
† Transport for London is a website that provides information on all forms of transport in London

data sources. Such techniques are based on data source composition and manipulation operations considered useful by users of mashup tools, which are often used in sensemaking activities.

- *Collaborative mobile mashup.* The proposed composition paradigm and the implemented techniques can be considered as a solution to support the co-located collaborative creation of mashups on users' own mobile devices, a solution scarcely investigated until now. Thanks to the proposed techniques, our work addresses this lack by allowing a group of co-located users to compose mobile app content.
- *Design indications*. During the three-step research study, we collected several suggestions for spatial-aware cross-device interactions. There were fundamental and far-reaching themes that were repeatedly brought up by participants or occurred during the studies. We summarize these design indications by proposing two themes and discuss their implications for design and future research.

1.2. Article organization

The composition paradigm implementing the spatial-aware cross-device (SACD) techniques reported in this article has been conceived along a three-step research study (Elicitation, Formative Evaluation & Refinement, and Comparative Evaluation) involving a total of 65 users in 18 groups. The main phases of the study are summarized in Figure 1 (which also shows System Implementation) and then described in the article.

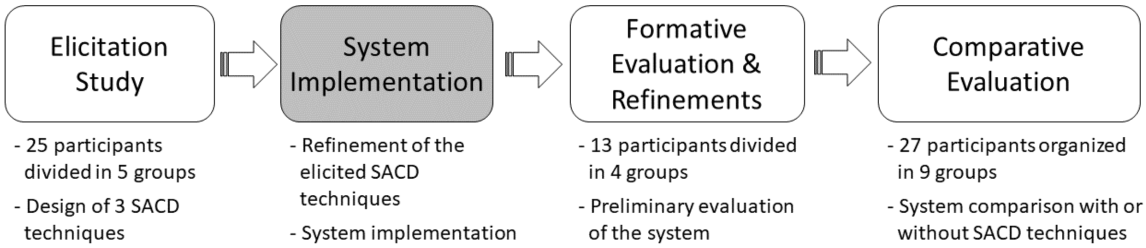

Figure 1. A schematic representation of the workflow process describing the different phases of the studies.

The article is organized as it follows. Section 2 introduces some background concepts about mashup and cross-device interaction techniques. Section 3 reports the elicitation study performed to design the spatial-aware cross-device techniques. Section 4 illustrates the spatial-aware cross-device techniques we designed starting from the elicitation study results. Section 5 presents technical details of the system that implements the elicited techniques. Section 6 describes the formative usability evaluation of the proposed techniques, while Section 7 illustrates the comparative evaluation, where the system versions with and without the elicited techniques were compared. Section 8 sketches some design implications. Finally, Section 9 draws our conclusions and outlines our future work.

2. Related Work

This section illustrates related works in the two main areas addressed by the research reported in this article, i.e. collaborative mashup and cross-device interaction for sensemaking.

2.1. Collaborative Mashup

Mashups are data-centric Web applications that assist unskilled users in easily composing heterogeneous resources [Daniel and Matera 2014]. In the last 25 years, different mashup tools have been proposed, but almost all support single user interaction only. One of the pioneers was *Yahoo!Pipes* [Pruett 2007], a visual editor that provided access to services and operators that could be combined into a canvas pane through drag and drop actions. In particular, services and operators were shown as visual modules that users could link by means of 'pipes'. Moreover, Yahoo!Pipes provided a useful debugger for the users to inspect Pipe output at various stages in the Pipe. The composition results could be exported in other Web sites. A completely different approach has been implemented in *DashMash*, a Web mashup platform that, by means of an event-driven paradigm and without distinction between editing and execution time, allows to create and synchronize Web services [Cappiello et al. 2011]. Another composition paradigm has been introduced in *NaturalMash*, a tool that allows users to indicate, using a natural language, services they want into their application and how to orchestrate them [Aghaee and Pautasso 2014]. In order to ensure the accuracy of queries, NaturalMash constraints the user to using a limited vocabulary and grammar. Another mashup platform, *EFESTO*, has been designed to enable end users to explore information by creating interactive workspaces [Desolda et al. 2015]: within a Web composition environment, end users dynamically create “live mashups” where relevant information, extracted from heterogeneous data sources – including the Linked Open Data [Desolda 2015] – is integrated according to visually defined queries. With respect to other mashup platforms, EFESTO privileges visual composition paradigms that accommodate the end-user mental model for a lightweight data integration within Web workspaces [Aghaee and Pautasso 2014; Cappiello et al. 2011].

Despite a wide proliferation of mashup tools, only some of them allow remote collaboration [Ardito et al. 2014a; Jung 2012] or distribution of the mashup execution across different devices [Husmann et al. 2014; Kovachev et al. 2013]. For example, *Activiti* is a lightweight workflow and Business Process Management (BPM) platform that supports users, possibly organized in groups working at distance, in defining BPM diagrams that can be validated and executed to create mashup [Alfresco_Software 2018]. Another example is *ContextGrid*, a contextual mashup-based collaborative (co)-browsing platform, which provides online users with various knowledge-sharing services [Jung 2012]. This platform supports groups of users in composing mashup integrating heterogeneous pieces of information collected by various Open APIs, and assists users in selecting partners they have to collaborate with.

To the best of our knowledge, no further previous work has investigated the benefits of collaboration of co-located users in performing mashup. Our research aims to cover this lack by allowing a group of co-located users to mashing-up mobile app content by moving mobile devices into different positions on a desk and by performing touch gestures on their displays.

2.2. Cross-device Interaction for Sensemaking

Over the last years, several solutions for cross-device interaction have been proposed. One of the most important aspects that characterize such solutions is the type of devices involved in the interaction. In most cases, just mobile devices are involved [Chen et al. 2013; Hamilton and Wigdor 2014; Hinckley et al. 2004; Lucero et al. 2011; Rädle et al. 2015], but more complex settings also allow cross-device interaction between PCs, mobile devices and large displays in hybrid environments [Andrews et al. 2010; Chung et al. 2014; Homaeian et al. 2018; McGrath et al. 2012; Reetz et al. 2006; Rekimoto 2004; Rekimoto and Saitoh 1999; Seyed et al. 2012; Voida et al. 2005; Wallace et al. 20132013; Wobbrock et al. 2009]. However, a recent work has demonstrated that users are also able to collaborate with tablet-sized devices, without the need of large shared displays [Zagermann et al. 2016].

Another important characteristic is the method used to set-up and start the cross-device communication. Different approaches have been investigated, for example using a master device [Chung et al. 2014; Hamilton and Wigdor 2014], bumping devices [Hinckley 2003a; Hinckley 2003b; Lucero et al. 2011], exploiting NFC technology [Hardy and Rukzio 2008], attaching QR codes to the devices that are scanned and recognized by the camera of the other devices [Alt et al. 2013], tracking devices with a camera mounted on the desk [Turchi et al. 2017] or on the ceiling [Reetz et al. 2006; Rekimoto and Saitoh 1999] and performing synchronous gestures [Chen et al. 2013; Hinckley et al. 2004; Rekimoto 2004]. Although these solutions enable cross-device interactions, they do not foster a natural interaction and are not adequately blended in the environments. For example, the use of a master device compels users to execute the procedure for adding and removing devices whenever they need to establish/remove links between devices [Chung et al. 2014; Hamilton and Wigdor 2014]; QR codes have to be attached to the device [Alt et al. 2013]; NFC technology is currently not widespread. A recent approach, *SurfaceConstellations*, tries to overcome some of these problems [Marquardt et al. 2018]. It consists of a modular hardware platform for linking mobile devices to easily create cross-device workspace environments. It implements a solution for capacitive links between tablets for automatic recognition of connected devices and a web-based tool for creating new setups.

Few works investigated the problem of spontaneous device binding from a user perspective. *EasyGroups* proposes a system whose design is based on the results of a guessability study, which involved non-technical participants with the aim of finding out how people connect devices in a group configuration. A leader creates the group by starting the application and then adds other persons into the group by bringing their devices to touch. Another recent work elicited the mental model of users that need to establish connections between devices [Chong and Gellersen 2011]. Authors elicited device association actions from non-technical users, collecting 37 different device combinations. The results revealed that there is no a single category that dominates what people perceive as a suitable spontaneous action for associating devices. Such combinations were grouped into five dominant categories: Search & Select, Proximity, Button Event, Device Touch, and Gesture. In order to create gesture sets that are consistent across different device types, in [Dingler et al. 2018] the authors propose a method that includes 1) gesture elicitation on each device type, 2) consolidation of a unified gesture set, and 3) final validation by calculating a transferability score.

Another important aspect of cross-device interaction concerns the supported tasks. Cross-device techniques typically permit simple tasks, for example transferring objects (e.g., photos [Lucero et al. 2011; Lucero et al. 2010], data items

[Hamilton and Wigdor 2014; Rädle et al. 2015] or documents [Hinckley 2003a]) across devices. A more sophisticated approach, *Pocket Transfers*, proposes interaction techniques to transfer content from situated displays to a personal mobile device while keeping the device in a pocket or bag [Mäkelä et al. 2018]. Another typical task in cross-device interaction is the distribution of parts of Web applications across multiple displays [Cappiello et al. 2011; Chen et al. 2013; Yang and Wigdor 2014]. However, the full potential of cross-device interaction could be still undiscovered, since few works have addressed complex sensemaking tasks. Typically, sensemaking processes are supported by complex systems that involve PCs or large displays (e.g., see [Andrews et al. 2010]), while few systems exploit only mobile devices. An example is *VisPorter*, a visual analytic system for sensemaking, that enables seamless cross-device activities through lightweight touch interactions performed on multiple large displays and mobile devices that can be fluidly connected [Chung et al. 2014]. *Conductor*, another system exploiting mobile devices, implements a set of interaction techniques designed to enable single-user, cross-device interaction supporting information sharing, task-chaining across devices, and session management [Hamilton and Wigdor 2014]. Another example of mobile-device-based system supporting sensemaking is *Co-Curator*, a mobile app that enables collection and sharing of information in face-to-face meetings during the early stages of collaborative design projects [Porcheron et al. 2016]. By using Co-Curator, users first collect their materials presented on a personal timeline on their mobile devices; later, they share with the group the personal timelines and engage in a collaborative task.

Differently from previous cross-device sensemaking systems, the techniques we propose in this article support *multiple interactions of a group of users* (instead of a single user, e.g., [Hamilton and Wigdor 2014]). The most important peculiarity of our proposal is the spatial-aware feature, since we suppose that cross-device interaction is more usable and less demanding than spatially-agnostic approaches. Indeed, by including the space dimension in the interaction mechanisms, users can bring down to workable time and memory demand the execution of sensemaking tasks, thus increasing reliability and number of tasks managed at once [Kirsh 1995].

3. Elicitation study

Given the lack of approaches for collaborative information seeking and sensemaking tasks to combine data from different data sources, an elicitation study was performed in order to understand how users would perform data composition operations by interacting with their mobile devices using spatial-aware cross-device techniques. In addition, how users perform such data composition operations by means of touch gestures and/or arrangement of devices on a desk was observed in order to identify design implications.

According to [Morris et al. 2014], in order to collect as much as possible significant ideas from participants, we required them to work in groups. When participants are enabled to build upon one another's ideas and asked to decide on a single preferred design solution, more reflection and discussion is expected, as well as the elicitation of more diverse opinions about the possible designs. We organized focus groups in which small groups of participants engaged in the elicitation exercise jointly. Similar to [Marquardt et al. 2012; Voida et al. 2005], our sessions contained an element of co-creation beyond pure elicitation.

As described later, the study enabled participants to provide novel, elaborated ideas, including some details on physical input and visual output. The study protocol was preliminarily assessed by involving two groups of four users each.

3.1. Participants

We involved a total of 25 participants (6 female), aged between 20-28 years ($\bar{x}$ = 22.6, SD = 1.95), randomly divided into 5 groups. Participants were recruited from the third-year students of the bachelor degree course in Computer Science. We involved Computer Science students because they had acquired some experience in system design thanks to the Human-Computer Interaction course they attended in the previous semester. However, in order to avoid or reduce the bias of previous knowledge of similar tools, we recruited participants who were familiar with smartphones and tablets, but they had no experience with mashup or cross-device techniques. A pilot study was performed involving further 3 participants in order to validate the study procedure and to identify possible threats.

3.2. Task Scenario

In order to facilitate the participants' understanding of the usage context, we adopted a scenario-based design. As underlined by [Rosson and Carroll 2003], designers need to be constrained during the design, and scenarios allow them to be more focused on prospective users and their needs.

To identify a set of significant sense-making tasks to be included in the scenarios, we started by identifying a set of data-composition operations to be performed by means of SACD techniques. As seed of this phase, we took inspiration from the most widespread data source composition operations implemented in mashup tools [Daniel and Matera 2014] and that are typically used in traditional sensemaking activities (see, for example, [Ardito et al. 2014b; Daniel and Matera 2014]). In technical terms, they are: *union* of data sources, *join* of data sources, and *data visualization*. The union operation produces one dataset obtained by combining the datasets returned by two or more compatible data sources. The join operation, also called 'merge' in many mashup tools [Daniel and Matera 2014], defines a data synchronization schema between two data sources A and B, so that B is queried by using an instance of A; this synchronization is achieved by linking an attribute of A with the input of B. Finally, the data visualization operation shows the dataset returned by a data source according to a visualization technique.

Starting from these operations, we identified the following three collaborative sensemaking tasks, involving the union, join and data visualization operations, respectively:

T1) querying multiple data sources, each displayed on a different device, typing a keyword just once on one device;
T2) querying the data source on the device B with portions of text displayed on the device A;
T3) visualizing on a target device T the data coming from a source device S; the visualization offered on T (e.g., map) is different from that on S (e.g., list of items).

Starting from these tasks, we elaborated three scenarios the participants have to follow during the study. With the aim of bringing out inconsistencies in the solutions proposed by participants, a fourth scenario was proposed. It was more complex and required also the execution of both tasks T1 and T3. Indeed, during the pilot study some participants proposed the same interaction technique for performing different operations (for example, placing two devices close each other for executing both the tasks T1 and T2), but they did not realize that this solution, if implemented, would produce a non-deterministic behaviour not manageable by the system.

In the first scenario (including task T1), the participants had to find videos of the "U2" rock band by querying the sites YouTube, Vimeo and Dailymotion, each displayed on a different device. They had to execute the query just once on one of the three devices, avoiding re-typing the same query on the other devices.

In the second scenario (including task T2), the participants were asked to use the Last.fm site on a smartphone to search for upcoming concerts in London. When a concert was chosen, they had to find details (e.g., recordings, photos) about the concert singer on Wikipedia, which was available on a second smartphone.

In the third scenario (including task T3), the participants interacted with the Zoopla site to look for a property in different districts of London. Zoopla provided a list of properties and the participants had to visualize them as pins on Google Maps available on a tablet.

Finally, inspired by Sherlock's scenario presented in Section 1, the fourth scenario (including both task T1 and T3) required looking for an apartment in different districts of London using Zoopla. Further information on pollution and public transport in those districts, retrieved by using the same keywords (e.g., London Stratford) and visualized by two sites available on two further smartphones, had to be taken into account (T1). Finally, apartments, air pollution sensory-stations and bus/metro stations had to be visualized on Google Maps displayed on a tablet (T3).

3.3. Procedure

The study was conducted by two HCI researchers on two consecutive days in a University laboratory. It consisted of 5 sessions, one for each group. Three sessions took place the first day. In every session, the group sat around a table and was provided with mobile device paper prototypes enabling the task scenarios as well as sheets of paper and markers for sketching their suggestions. Each participant was also provided with a sheet of paper reporting the four scenarios (see Figure 2).

An HCI researcher gave a 10-minute presentation to explain the motivation for composing data coming from different sources. In order to illustrate and make participants more familiar with spatially-aware interaction, the researcher briefly described HuddleLamp and showed a 3-minute video demonstrating some examples of its usage. To avoid any bias in the participants' proposals, possible solutions for composing data sources were not shown. After reading aloud and commenting the first scenario, the researcher asked participants how they would perform the scenario activities and also specified that they were completely free to propose any data source composition idea, with or without spatial-aware features. To prevent participants from being forced to propose something they were not convinced of, they were free to produce as many ideas as they wish. The researcher stimulated participants to elaborate new interaction ideas, which were also expressed by sketching new paper prototypes or demonstrated by using the available paper prototypes (e.g., a swipe gesture from one device prototype to another). The researcher also encouraged the discussion on positive and negative aspects of the suggested solutions. Before moving to the next scenario, the group had to agree on the interaction techniques they were proposing for carrying out the assigned composition task. The same procedure was repeated for the other three scenarios. The second researcher took notes. Each session lasted on average 70 minutes and was also audio-video taped. At the end of the session, participants filled in a post-test questionnaire. It was composed of 19 questions: 11 questions aimed at collecting participant's demographic data and determining their expertise with mobile devices, programming, data retrieval and composition; 4 questions investigated participants' understanding of and comfort with the proposed tasks; 2 questions addressed the main dis/advantages of the proposed interaction techniques; 2 questions addressed the pros and cons of the spatial-aware features for mobile devices.

Figure 2. A group discussing and working with paper prototypes during the elicitation study.

3.4. Data analysis

The data analysed in the study were collected through: 1) a set of notes taken by the researchers in the study sessions; 2) the audio/video recordings of participants' discussions; 3) the sketches drawn during the sessions; 4) the answers participants gave to the questionnaire.

The set of notes collected in the field was substantially extended by video-analysis. The two researchers iteratively transcribed the videos, literally noting down all intelligible speech. The transcriptions were analyzed following the thematic analysis [Braun and Clarke 2006] and the analysis results were double-checked for reliability, leading to an initial value of 90%. Discrepancies were solved by discussion. The answers to the open questions of the questionnaire were analysed through the affinity diagram technique proposed in [Preece et al. 2015].

3.5. Results from the scenario discussion

A triangulated analysis of the researchers' notes, audios of participants' discussions, groups' sketches and videos leads to the following description of the participants' proposal for performing the tasks included in the scenarios.

Task 1: all the five groups involved in the elicitation study agreed that *spatial proximity*, i.e., putting devices close to create a *physical group*, was the best solution for querying multiple data sources, each displayed on a different device. The proposed task flow was: 1) put the devices close to each other in order to create a group and then, 2) query one of them to automatically *broadcast* the same query to the other devices. Reporting on the words of one participant, "*an idea is that, when I'm executing a search with a keyword on a device, the other devices that are close to my own simultaneously perform a search by using the same keyword*". Two groups also suggest to add/remove a device from a group by taking it close/far to/from the group. As a further solution, similar to the synchronous gesture proposed in [Hinckley 2003a], two groups proposed *device bumping*, i.e., colliding devices to create a virtual group that can be queried as in the previous case.

Task 2: all the groups suggested solutions that bring to *directional flick* as the most suitable technique to express that a piece of text has to be used for querying the data source displayed on another device. The directional flick is a spatial-aware gesture performed on the source device display for "launching" the selected portion of text in the direction of the target device, where it will be automatically used for querying the displayed source (an interaction similar to the gesture described in [Reetz et al. 2006]). For example, a participant said "*While I'm searching a musical event on Last.fm running on a tablet, I can open*

Wikipedia on another device and search singer information on Wikipedia by launching the singer name from the Last.fm tablet to the Wikipedia device, without typing the singer name on Wikipedia". Two groups also suggested that this task could be performed by touching, for a couple of seconds, a piece of text to activate a *contextual menu*, where they can choose the target device from the list of devices on the desk. This alternative solution is a spatial-agnostic interaction similar to the one proposed in [Hamilton and Wigdor 2014].

Task 3: all the groups proposed different solutions on how to visualize on a target device data coming from a source device. For example, Group 1 decided for bumping the two devices, a synchronous gesture as the one proposed in [Hinckley 2003a]. Groups 2 and 3 opted for a button on the target device to open a popup window where the user can choose the source device among the ones on the desk. For example, a participant said "*After opening Zoopla on a tablet, I open Google Maps on another device and here I tap a button to open a window that lists all the devices on the desk. From this list I can choose a device providing data visualizable on Google Maps, for example Zoopla, to plot the Zoopla houses as pins on the map*". Group 4 and 5 decided for spatial proximity, but this solution was already proposed for the *Query Broadcasting* task. Such an inconsistency clearly emerged during Scenario 4, which put together tasks T1 and T3.

3.6. Results from the online questionnaire data

At the end of each session, participants filled out an online questionnaire including 19 questions. The results obtained from the eleven questions regarding participants' demographic data and expertise with mobile devices, programming, data retrieval and composition were used for describing in details the participants' profile, as reported in Section 3.1.

The analysis of the four questions on participants' understanding of the study design, each consisting of a Likert scale that ranged from 1 to 7 (1 very easy – 7 very difficult), revealed that participants did not have difficulties in realizing what they needed to do during the execution of the four tasks (T1 $\bar{x}$ = 2.12, SD = 1.36; T2 $\bar{x}$ = 2.4, SD = 1.44; T3 $\bar{x}$ = 2.32, SD = 1.41; T4 $\bar{x}$ = 2.8, SD = 1.5).

The last four questions regarded respectively the main dis/advantages of the proposed interaction techniques (2 questions) and the pros and cons of the spatial-aware features for mobile devices (2 questions). Regarding the advantages of the proposed solutions, in general participants thought that properly designed gestures would be perceived natural and powerful and would adequately support the manipulation of a large amount of data that is a task typically performed by technical users with more complex tools. In addition, they said that the design of user interfaces would benefit from replacing buttons, menus and other user interface components with spatial-aware cross-device techniques. Lastly, they highlighted that collaboration possibilities enabled by these techniques represent an added value, because multiple users can actively collaborate in sensemaking activities by just putting his/her own device on the desk, thus being quickly included in group discussion.

Regarding the disadvantages, we collected important hints for the design of the spatial-aware cross-device techniques. First, the cognitive load due to gesture memorability and ambiguity has to be considered. Then, users have to be supported during the join operation between devices both in selecting the right target device and in getting aware that their own device has been joined by another one. Lastly, the implementation of mechanisms to freeze the synchronization between devices was suggested, so that devices can continue to be part of a group even if removed from the desk.

Regarding the spatial-aware feature, the participants found interesting the possibility to easily establish connections between different devices, and consider it excellent to support collaborative co-located tasks.

4. Spatial-aware cross-device techniques

In order to overcome the high level of abstraction of the SACD techniques emerged during the elicitation study, we revisited and improved the proposed solutions. For example, for the union operation (i.e., task T1) many participants suggested putting close all the involved devices to create a physical group, but they did not reflect on which should be the suitable distance between devices to consider them as a group, or if the users should receive a feedback to inform if the devices are part of a group or not. In the next sub-sections, we describe how, in implementing the final system, we bridged this lack of details. The described techniques also include some improvements emerged during the formative evaluation, as better described in the following.

From now on, we call the SACD techniques for performing union, join and data visualization *Query Broadcasting*, *Flying Join* and *Aggregation&Visualization*, respectively.

4.1. Query Broadcasting

The final solution to query multiple data sources each displayed on a different device, by typing a keyword just once on one device, was to implement the spatial-aware technique based on the spatial proximity of the devices: for broadcasting a query performed on one device to the other ones, users put close the involved devices (see Figure 3). In order to define the final design of the Query Broadcasting technique we had to elaborate on three aspects that lightly emerged during the elicitation study.

The first one regarded the feedback about device grouping. To notify users that a device is part of a group, display borders of the grouped devices are highlighted in orange, as shown in Figure 3. As soon as a device is moved close to the others enough to be considered part of a group, the orange borders appear. This also improves the system status visibility, because all users can easily understand which devices are grouped.

The second aspect was the technique to broadcast the query. Different alternatives were expressed by the participants. For example, one of them said: “*I like that when I move a device close to another one the second device automatically executes the same query already performed on the first device*”. However, this gives rise to the following problem: let us suppose that on two devices, not yet grouped, two different queries have been executed. What happens if later they are grouped? Which one broadcasts its query to the other one? In the final design, we opted for broadcasting any query at grouping time, i.e., queries are broadcasted only after the group has been established.

The third aspect we investigated was the distance threshold between the devices to consider them a group. Some participants suggested that a small distance should be kept between the devices; other participants said that devices should adhere each other. However, we did not consider this second possibility, because of our system would not be able to recognize the devices if there is not a distance of at least 0,5 centimetres between them. Taking into account that up to five tablets can be positioned over the desk area recognized by the system (of about 1.0×0.6m), we empirically established that devices are grouped when the distance between them is in the range 0.5 – 3 centimetres.

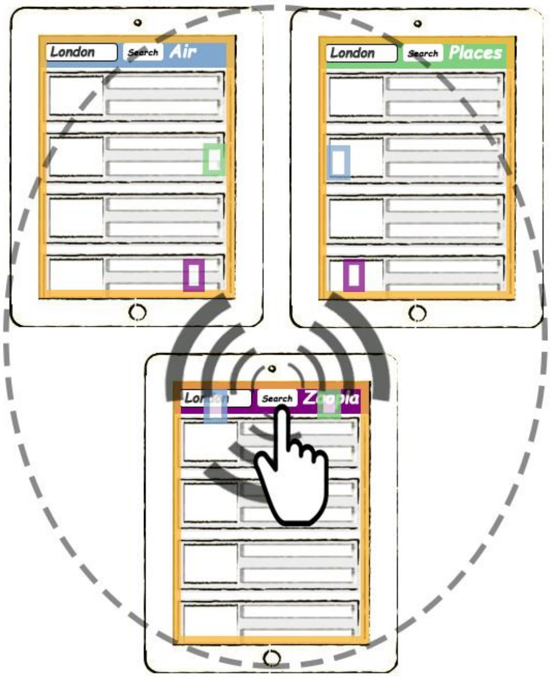

Figure 3. Example of *Query Broadcasting*.

4.2. Flying join

To query a data source available on a device B with portions of text displayed on a device A, participants proposed two solutions, *directional flick* and *contextual menu*, similar to the techniques to move content across devices compared in [Reetz et al. 2006]. For large targets, the directional flick was significantly faster than radar (a technique very similar to the contextual menu proposed by our participants), but was inaccurate for small targets. *Edge Bubbles*, presented in [Rädle et al. 2015], enhances the flick technique; it was shown that it outperforms other methods like contextual menu and radar. Edge Bubbles consists in coloured semi-circles around the edges of the screen, which act as visual proxies for remote devices and indicate the direction in which the remote devices are located on the desk. The locations of the bubbles are defined by imaginary lines connecting the central point of the source device and the central point of the target devices. Each bubble is located where this imaginary line intersects with the edges of the local screen. The positions of the bubbles are updated in real-time and thus always reflect changes in the physical configuration of the devices. In the Edge Bubble technique, dragging and dropping an item onto one of the edge bubbles means copying the dragged item to the target device.

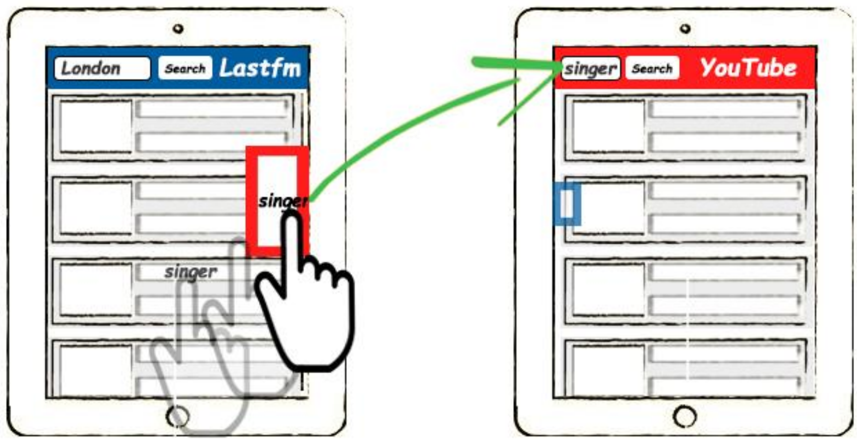

Figure 4. Example of Flying Join.

We adopted the Edge Bubble solution to implement the *Flying Join*. In particular, in our system dragging and dropping a piece of text onto one of the edge bubbles generates a query on the target device with the dragged text as the keyword. For example, in Figure 4 YouTube is queried by dragging and dropping a specific singer's name into the Last.Fm red rectangle.

Participants' comments and utterances collected during the formative evaluation (see Section 6) gave us important indications on how to improve this technique. For example, edge bubbles affordance was enhanced by representing them as rectangles instead of semi-circles, thus resembling the tablet or smartphone shape (see Figure 4). Furthermore, due to the difficulties participants had in dragging a large piece of text onto the bubbles, we decided to provisionally redouble the dimension of a bubble when the dragged text is approaching it. In the example of Figure 4, the dimension of the red rectangle has been redoubled because the singer's name has been dragged on it.

4.3. Aggregation&Visualization

The third composition technique related to the data visualization operation consists in synchronizing one or more source devices S_i, $1 \leqslant i \leqslant n$, and one target device T, so that data coming from S_i are visualized in T. It is called *Aggregation&Visualization* because it allows the visualization on T of data gathered from a single device or an aggregation of devices previously grouped with the *Query Broadcasting* technique. The aggregated data are visualized according to the visualization provided by T, for example, Google Maps.

In the end, we implemented the proposal of Groups 2 and 3, i.e., a menu on the target device T to select the source device S on the desk from which to visualize the data. Moreover, as required by each group, we allowed the selection of not only a source device, but also devices grouped by using the *Query Broadcasting* technique. When a user opens a site on T that provides a specific visualization (for instance, Google Maps), in the title bar the button *Decant*[‡] is available (see Figure 5a). By clicking this button, a pop-up appears and lists all the devices on the desk, each identified by the name of the site it is executing. If multiple devices have been grouped for query broadcasting, the name of the group, which has been automatically created by the system by concatenating the site names, is displayed. The user chooses the source devices from the list. From now on, the target device T visualizes the data gathered from the source devices S (Figure 5b). Any data updating on S is

[‡] We have used 'Decant' as metaphor of pouring and mixing wine in another container, where it assumes the shape of the target container and the new flavour due to the mixing.

immediately propagated on T. The synchronization between T and S can be stopped by using the menu in T or by taking away S from the table. In addition, as reaction to a tap on a specific item in the source devices S, the same item is highlighted on the target device T. For example, if Google Maps is displayed on T, the map is centred and zoomed at the location of the item tapped on S. This implementation exploits spatial awareness system features, since T is aware of and reacts to all the devices currently on the desk.

(a)

(b)

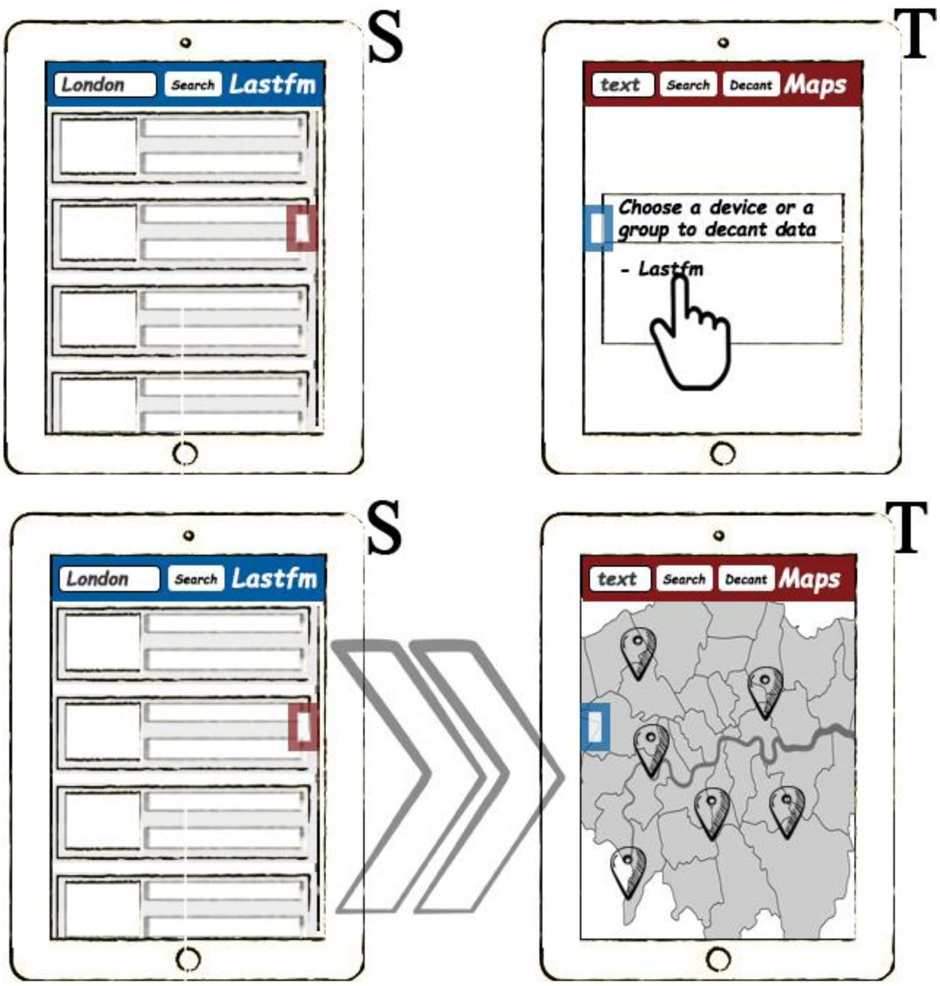

Figure 5. Example of Aggregation&Visualization: (a) selection on device S of Last.fm as source; (b) visualization of Last.fm items as pins on Google Maps on device T.

5. Implemented System

The overall system installation consists in i) setting up HuddleLamp [Rädle et al. 2014], i.e. the tool for tracking the devices on the table and make them aware of the locations of all the others; ii) deploying a Web server where our application runs; iii) installing a Google Chrome plugin we developed on the mobile devices, as shown in Figure 6.

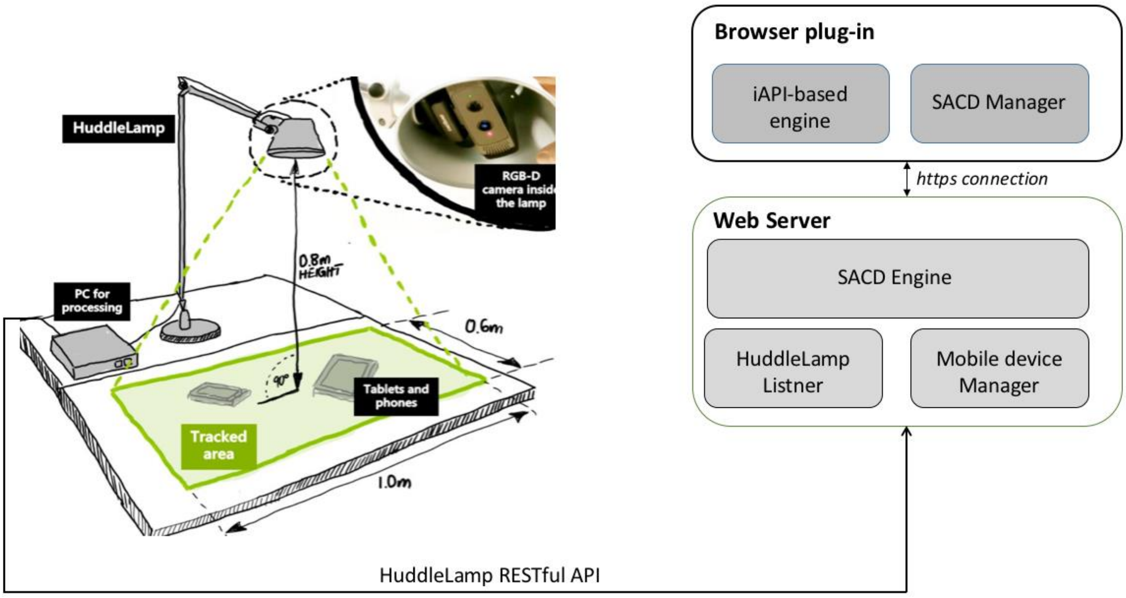

Figure 6. Overview of the final system including hardware and software modules

HuddleLamp has been chosen for its flexibility, technical equipment simplicity and powerful features for enabling cross-device interactions. Other technologies would be adopted, but they typically require the installation of specific hardware in the environment or on the devices (e.g., [Reetz et al. 2006; Voida et al. 2005]), as well as the installation of software to manage the registration of devices [Hamilton and Wigdor 2014] or to offer specific functionality [Dachselt and Buchholz 2009]). Thanks to HuddleLamp, no hardware or software needs to be installed on the mobile device, since users have just to open a Web site. HuddleLamp just requires the installation of a desk lamp to hold up a commercial 3D RGB camera connected to a computer, where the HuddleLamp software runs. In this way, it makes possible to connect mobile devices that have no prior knowledge of each other in a fast and easy manner.

In our system setup, connections between devices are established by simply placing/removing devices on/from a desk. When mobile devices are on the desk, initially they display a QR-code that HuddleLamp uses for their first identification. Then, the QR-code disappears and, from that moment on, HuddleLamp continuously tracks the devices on the desk, streaming their information about location, size and orientation to third-party applications through a RESTful API (see Figure 6). Thus, there is no need that the mobile devices are equipped with additional custom-built sensing hardware or markers. This is an important advantage promoting the adoption of our system in real contexts. Other solutions for cross-device interaction require the installation of either hardware in the environment [Reetz et al. 2006; Voida et al. 2005] or on the devices.

In order to exploit HuddleLamp data for implementing our SACD techniques, we developed a Web server application by using the Meteor framework [Meteor Development Group Inc. 2016]. Meteor has been chosen because it is an ultra-responsive framework, which means that changes made by a user on a device are instantly visible on the connected devices, without the unprofessional lags feeling that would result from waiting for a round trip to the server. As shown in Figure 6, our Web server application acts as a bus that connects the devices on the desk. It consists of three modules. The first one, *HuddleLamp Listner*, receives the HuddleLamp API stream, decodes its data and sends the device information to the *Mobile Device Manager*. For each device on the desk, the *Mobile Device Manager* creates a JavaScript object characterized by attributes reporting information on device size, position and orientation. Finally, the *SACD Engine* orchestrates the devices' behavior according to the SACD action performed by users. It implements a JavaScript function called *dispatcher*, remotely invoked by the mobile device where the SACD action is performed, and three functions (*Flying_Join*, *Query_Broadcasting*, *Aggregation&Visualization)* one for each SACD technique. The dispatcher has three parameters: the SACD name and two variables whose type depends on the performed action. When invoked, the dispatcher activates the function related to the performed SACD action. For example, in case of a Flying Join, the dispatcher activates the *Flying_Join* function passing two parameters, i.e., the query string and the name of the target device where the query string is sent. Similarly, in case of a query broadcasting action, the dispatcher invokes the *Query_Broadcasting* function passing the query string and an array of strings related to the queried devices, in order to send the query keyword to them. Lastly, in case of Aggregation&Visualization action, the dispatcher activates *Aggregation&Visualization* function passing an array of data to be shown (codified in JSON format) and the name of the target device where data are sent.

On each mobile device, a Google Chrome plugin we develop is connected to the Web Server and enables the SACD techniques. The plugin is in charge to extend the Web sites with UI elements that support the SACD techniques. In particular, it visualizes the orange border indicating that the device is grouped for query broadcasting; in order to support the Flying Join, it turns Web page content into interactive artefacts and it plots the EdgeBubbles according to the information sent by the *Mobile Device Manager* module. In designing the plugin, we took inspiration from the UI-oriented approach reported in [Daniel 2015; Daniel and Furlan 2013; Nouri and Daniel 2016] where the authors proposed the *iAPI* (interactive API) as solution to enable programmatic access to UIs and interactive, live programming. The idea of iAPI is to equip pieces of UI of a Web page with dynamic and programmable behaviour, to foster reuse on the Web and enable a set of web-based integration scenarios like programmatically operating UIs, extracting data, extracting application logic, and cloning pieces of UIs. With respect to the architecture shown in Figure 6, these features are integrated in the iAPI-based engine.

Since our goal is designing and evaluating SACD techniques, in order to guarantee the same experimental setting among the different sessions and participants, in our evaluation studies we have chosen to use an accurate copy of a set of Web sites instead of the original ones. While study participants had to stay focused on the proposed tasks and scenario without external disturbs, often Web sites are characterized by annoying and unpredictable pop-ups (e.g., cockies policy) or pieces of UI (e.g., advertising banners), on which we do not have any control. They disturb the user attention and break the interaction flow. Another problem is that information frequently changes in Web sites, even several times during a day: it could be suddenly not possible to execute some tasks because the involved data are not available anymore, or they could change during the days of the experiment, thus do not allowing participants to act under the same conditions. By implementing a high-fidelity copy of the Web sites involved in the experimental tasks, we were able to avoid the interference of unpredictable pop-ups and banners and to “freeze” their data. According to the tasks to be performed by participants during the evaluations, we implemented a copy of the Zoopla, UK Air pollution, Google Places, Last.fm, YouTube, and Google Maps.

A video demonstrating the SACD techniques in the system used during the evaluation is available at the following private YouTube link https://youtu.be/rVx0y4F206w

6. Formative Evaluation

We designed a formative evaluation inspired by [Hamilton and Wigdor 2014], i.e., a study in which participants are required to perform real tasks using the system. Our study was performed during the interactive demo session of the International Symposium on End-User Development (IS-EUD) held in Madrid, Spain, during May 2015 [Desolda and Jetter 2015]. The session was open to both conference participants and external visitors and was widely advertised by the conference organizers before and during the conference days.

Since the main goal of this study was to understand how the proposed spatial-aware cross-device techniques support users - possibly without technical skills - in seeking and sensemaking tasks, similarly to [Hamilton and Wigdor 2014], we addressed three research questions:

RQ1) Are users able to perform co-located collaborative tasks by exploiting the proposed interaction techniques?
RQ2) Are users satisfied in performing co-located collaborative tasks using the proposed interaction techniques?
RQ3) Do users would prefer different interaction techniques for the three operations?

6.1. Participants and Design

We recruited 13 participants (5 female), aged between 23 and 64 ($\overline{x}$ = 32, SD = 13.74). More specifically, the participants were:

– 2 groups of technology experts (G1 with 3 participants, G3 with 4 participants), i.e., conference attendees who, according to the research papers they presented at the conference or to the comments they provided during the interaction, can be considered technology experts.
– 2 groups of non-technical users (G2 with 4 participants, G4 with 2 participants), i.e., no technical savvy conference attendees (e.g. researchers of other disciplines than Computer Science or Engineering) or external visitors.

Participants were intentionally divided into groups of technology experts and non-technical users because we aimed to investigate if the proposed composition paradigm fits equally the mental model of technical and non-technical users. Indeed, systems for data composition (e.g., mashup tools [Daniel and Matera 2014]) are typically most suitable for users with skill in computer programming, but our goal is to design SACD data composition mechanisms adequate for both technical and non-technical users.

The study was presented to each group of participants as a demo that gave them the opportunity to use the system to accomplish two scenarios. In Scenario 1, in line with the motivating scenario presented in Section 1, the groups were asked to act as friends planning to move to the UK. They had to look for a property in a UK city (using the Zoopla site), also considering factors like air pollution (using the UK Air pollution site) and property proximity to bus/metro stations (using the Google Places site). To evaluate the distance between properties, air pollution sensory-stations and bus/metro stations, they could use Google Maps to visualize the site results on the map. This scenario was designed to stimulate users in performing *Query Broadcasting* (for example, to query Zoopla, UK Air pollution and Google Places together using keywords like London, Liverpool, etc.) and *Aggregation&Visualization* (for example, to visualize results on Google Maps) activities.

In Scenario 2, participants were asked to act as a group of colleagues, who were in Madrid to attend a conference. They wanted to spend an evening at a music concert. Their goal was to find a concert in Madrid during the conference days using the Last.fm site. They could also use YouTube to search for videos related to the concert singer(s) and Google Maps to locate the concert venue. This scenario was designed to stimulate users to perform a *Flying Join*, for example, to search on YouTube for a specific artist previously retrieved in Last.fm (by drag & drop of a Last.fm artist name in the YouTube proxy), as well as to search for a specific concert venue (by drag & drop of a Last.fm location name in the Google Maps proxy).

The two scenarios were formulated so that they did not guide or constrain the user flow/interaction. Each group was required to search useful information following some general indications. In addition, the groups were not forced to use the SACD techniques but they could use them if considered useful to solve part of the scenario. The scenario execution order was counterbalanced across the four groups to neutralize learning biases. Participants were asked to verbalize their thoughts and comments according to the think-aloud protocol.

6.2. Procedure

The study took place in a quiet and isolated area in the main conference room where we installed the study apparatus 30 minutes before the interactive demo session (see Figure 7). Two HCI researchers were involved in the study. In particular, one researcher (facilitator) was in charge of introducing the participants to the study. In addition, since HuddleLamp sometimes suffers from detecting and tracking failures because of the environmental lighting, the facilitator was in charge of mitigating the problem acting as a "Wizard of Oz" (see, for example, [Dahlbäck et al. 1993]): when a failure occurred, he manipulated, by means of a laptop (visible in Figure 7), an interactive real-time representation of both the desk and the devices on it by moving the corresponding virtual device according to the participants' actions. Luckily, few detection problems occurred, thus participants were not aware of this workaround. The second researcher (observer) took notes about significant participants' behaviour or comments they externalized during the interactive session.

Each group interacted for about 60 minutes for a total of 4 hours. Every group followed the same procedure. First, each group member was asked to sign a consent form. Then, the facilitator gave a quick introduction to the three composition techniques by using a 5-minute video (no bias was introduced since the video showed different situations than the two experimental scenarios). Then, the actual interactive session started: the group was provided with four Apple iPads (9.7-inch display) on the desk, already set with the Safari browser connected to our Web application. The group was invited to perform the scenarios 1 and 2, reported on the two sides of a paper sheet, by using the available sites with or without the presented special-aware features, as they preferred. Finally, participants filled in an online questionnaire, which included the System Usability Scale (SUS) form with a further 22 statements. The SUS is a "quick and dirty" tool for measuring the system usability by means of 10 statements, rated by a 5-point Likert scale ranging from *Strongly agree* to *Strongly disagree* [Brooke 1996]. It was chosen because it is highly reliable [Bangor et al. 2008], technology agnostic (tested in the last 25 years on hardware, consumer software, websites, cell-phones, etc.) and effective also for evaluating the usability of modern technology [Brooke 2013]. We extended the SUS questionnaire with 10 new statements on the participants' background and 12 on the evaluation of the proposed composition techniques and the performed scenarios. Thus, the final questionnaire was composed of 32 questions.

At the end of the interactive session, some participants wanted to discuss with one of the HCI researchers, who is also the system developer, both technical and/or interaction details. They also provided hints for improving the system.

Figure 7. A group of participants and the facilitator discussing during the formative evaluation. The HuddleLamp camera attached to a flexible white arm and four tablets on the desk are visible.

6.3. Data Collection & Analysis

Different types of data were collected during the study. All the interactions were audio-video recorded to extract the participants' utterances and comments. The set of collected notes was extended by video and audio analysis performed by two researchers following the same procedure performed after the elicitation study (audio transcription, double-check, the thematic analysis [Braun and Clarke 2006]). The results of this analysis were double-checked for reliability, leading to an initial value of 85%. All discrepancies were solved by discussion.

6.4. Results

6.4.1. System Usage and User Behaviour

The qualitative data collected with notes and audio-video analysis provided important hints on participants' behaviour, new ideas and system improvements. One of the most significant problems observed was related to the *Aggregation&Visualization* technique, sometimes confused with *Query Broadcasting* by participants, as also confirmed by their utterances. For example, after put close Zoopla and Google Maps tablets, a member of G2 said: "*Why Zoopla properties are not visualized in the map?*". This problem occurred for three out of four groups. Indeed, when these three groups tried to visualize for the first time Zoopla data in Google Maps, they moved the Zoopla device close to the Google Maps device, thus communicating a *Query Broadcasting* instead of *Aggregation&Visualization*. This problem is in line with the results obtained during the elicitation study, where 50% of groups changed the visualization by moving the devices close and 50% by using a menu.

Minor problems were detected for the *Query Broadcasting* and the *Flying Join* technique. For the former, we observed that participants took some time to appropriate the spatial-aware cross-device technique. In fact, at the beginning of Scenario 1 two groups queried different devices by typing the same query on different devices. Only after some seconds, they realized that they could broadcast the query. For example, a member of G4 said: "*Ops, we can search for London more quickly by using the function shown in the video*".

Regarding the *Flying Join*, the observed problems were generated by some implementation constraints adopted in the system, which did not allow participants to perform some actions not foreseen by us. In particular, in the system users are enabled to drag one single piece of text (e.g., the property address from Zoopla) only onto the Google Maps and/or YouTube proxies. During the study participants tried to drag data of the pollution sensory-stations from the UK Air Pollution site onto the Zoopla proxy, in order to find on the Zoopla device all the properties around a non-polluted area.

We also collected important hints on how to improve the system usability. One of the most important is related to the proxy memorability. In fact, to support moving data across different devices, inspired by the “Edge Bubble” technique [Rädle et al. 2015], the proxies were shaped as coloured rectangles. The colours were the same of the site toolbars shown on the respective devices, but some participants didn’t notice or remember this relation. Two of them (i.e., G2 and G4) suggested adding the site name or logo inside the proxy.

The usability assessment was also performed through the analysis of the post-questionnaire data. In the following sub-sections, further details about the SUS scores (6.4.2), perceived usability of SACD techniques (6.4.3) and perceived satisfaction (6.4.4) are reported.

6.4.2. System Usability and Learnability

The 10 SUS questions provided useful indications about the perceived system usability and learnability. The SUS global score was 68.3 (SD = 10.6, 95% CI = [65.4, 71.2]) and in line with the average SUS scores (69.5) of one thousand studies reported in [Bangor et al. 2009]. In addition, according to [Lewis and Sauro 2009], we split the overall SUS score into two factors, i.e., *System Learnability* (considering statements #4 - need of external support - and #10 - need to learn a lot of things to use the system) and *System Usability* (all the other statements). The *System Learnability* score was 62.5 (SD = 25.5, 95% CI = [55.5, 69.4]), while the *System Usability* score was 69.7 (SD = 8.5, 95% CI = [67.4, 72.0]). Thanks to the analysis of the observer’s notes and video recordings, we can mainly attribute the lower learnability score to the difficulties that participants experienced with the *Aggregation&Visualization* technique.

We investigated the effect of the user expertise on the SUS global score, as well as on the SUS usability and SUS learnability scores (see Figure 8). Mann-Whitney U tests were run to determine if there were differences in the SUS scores between technical and non-technical users. In all the three cases, median scores were not statistically significantly different between technical and non-technical users (U_{SUS} = 22.500, p = .836; $U_{SUS\_usability}$ = 20.000, p = .945; $U_{SUS\_learnability}$ = 23.500, p = .731).

The satisfactory SUS scores obtained during the study, together with the equivalence of the technical and non-technical users’ scores, suggest an acceptable usability of the overall system, which fits the mental model of both technical and non-technical users, as it often does not happen with traditional web tools to compose data sources [Namoun et al. 2010; Wajid et al. 2011].

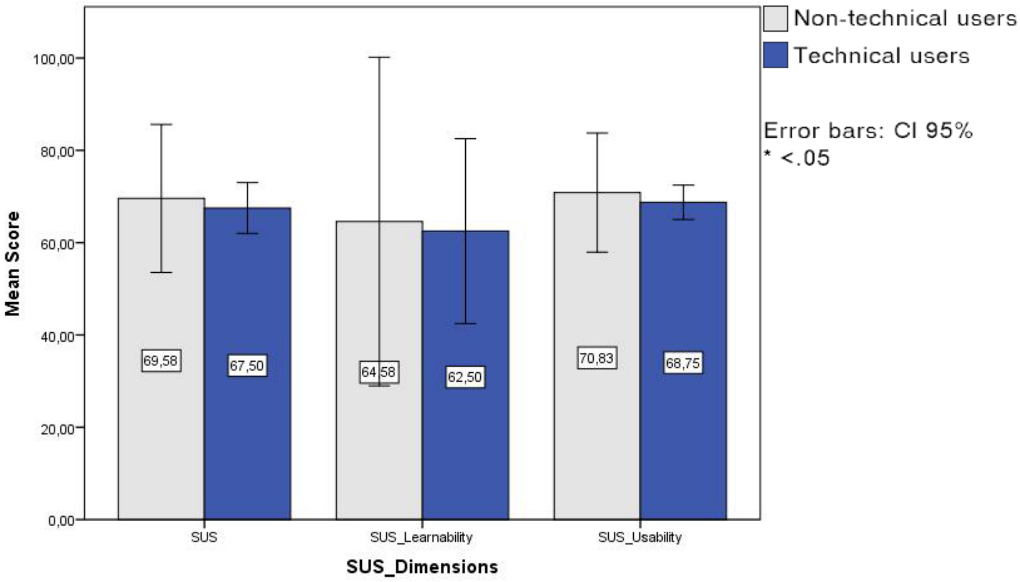

Figure 8. For each SUS dimension, a couple of bars depict the SUS scores of technical and non-technical users.

6.4.3. Cross-device Technique Usability

The administered questionnaire[§] also included 12 statements (2 open and 10 closed questions) to collect data on the perceived usability of some specific aspects, in particular on the techniques to perform the three composition operations and on the system used in the specific scenarios. The closed questions were formulated as a 5 -point Likert scale ranging from *Very difficult* (1) to *Very easy* (5).

The answers to the three closed questions addressing each interaction technique indicated a high level of perceived usability. The obtained values were: for *Query Broadcasting* $\bar{x} = 3.92$, SD = 0.86; for *Flying Join* $\bar{x} = 4.00$, SD = 0.81; *Aggregation&Visualization* $\bar{x} = 4.15$, SD = 0.90. These results are very encouraging and confirm what we also observed during the interactive session.

We also investigated the effect of the user expertise on the usability of the three composition techniques (see Figure 9). Mann-Whitney U tests were run to determine if there were differences between technical and non-technical users. In all the three cases, median scores were not statistically significant difference between technical and non-technical users ($U_{Query\_Broadcasting} = 22.500$, p = .836; $U_{Flying\_join} = 18.000$, p = .731; $U_{Aggregation\&Visualization} = 13.500$, p = .295).

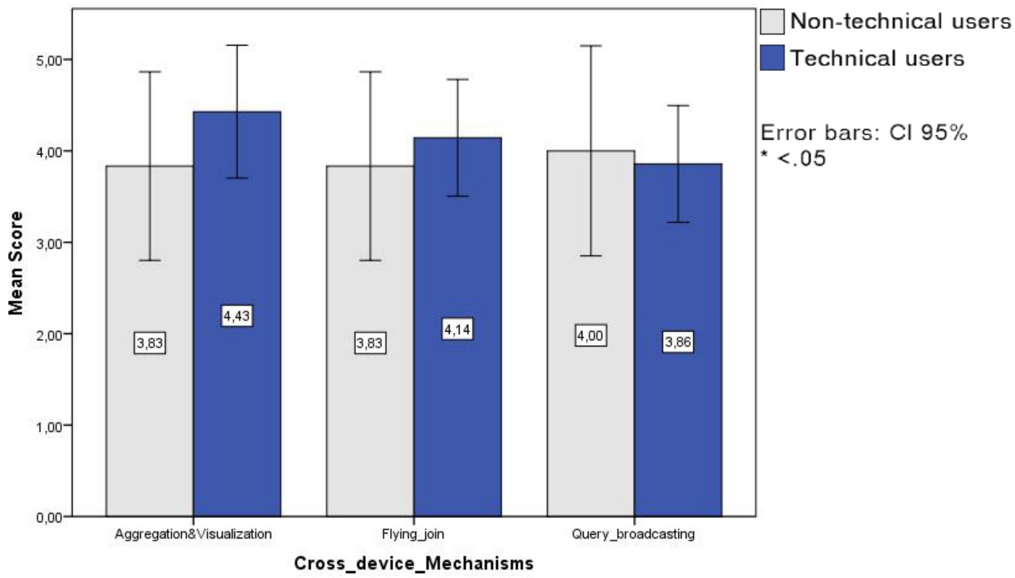

Figure 9. For each SACD technique, a couple of bars depict the scores of technical and non-technical users.

6.4.4. Perceived User Satisfaction

Besides evaluating each composition technique, we also assessed the perceived user satisfaction with respect to performing the two assigned scenarios. We asked the participants if they were satisfied with the *easiness* and the amount of *time* to complete the scenarios. As a result, for Scenario 1, the participants felt satisfied with the ease of completing the scenario ($\bar{x} = 3.76$, SD = 0.72) and the required amount of time ($\bar{x} = 3.76$, SD = 0.83). For Scenario 2, they felt even more satisfied about the ease of completing it ($\bar{x} = 4.14$, SD = 0.55) and the required amount of time ($\bar{x} = 4.23$, SD = 0.93). There was not a statistically significant difference for easiness and time between Scenario 1 and Scenario 2 ($t_{easiness}(24) = -1.519$, p = .142; $t_{time}(24) = -1.336$, p = .194). These results revealed that the participants thought that the system adequately supported the two different co-located collaborative sensemaking scenarios.

We also investigated the effect of the user expertise on the easiness and the time to perform the two scenarios (see Figure 10). A Mann-Whitney U test was adopted to perform this analysis. No significant differences emerged in all the cases ($U_{Scenario\_1\_easiness} = 19.000$, p = .836; $U_{Scenario\_2\_easiness} = 27.000$, p = .445; $U_{Scenario\_1\_time} = 23.500$, p = .731; $U_{Scenario\_2\_time} = 22.500$, p = .836).

[§] Available at https://goo.gl/forms/v29Dvt3cEmKpwVmC3

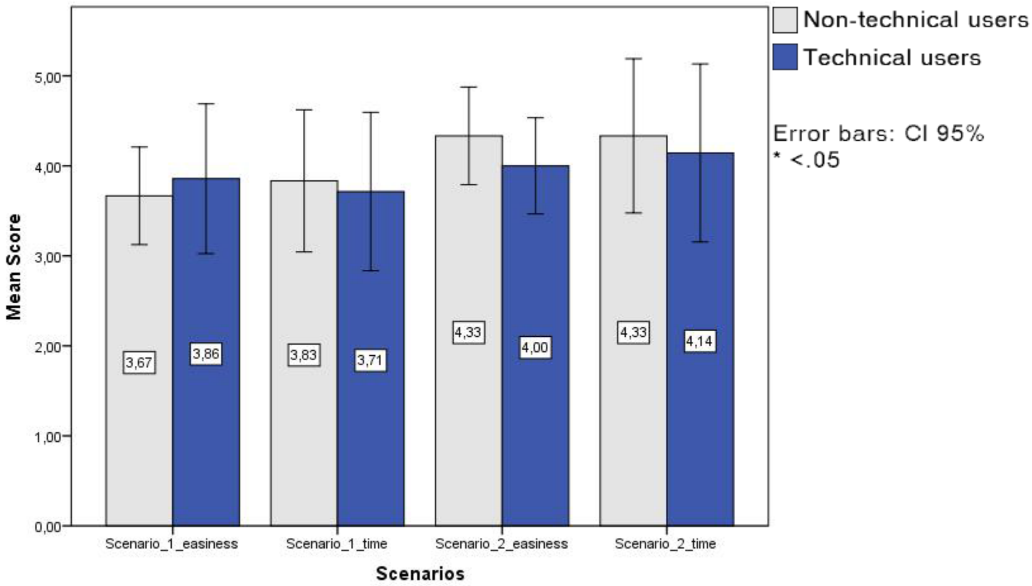

Figure 10. For each scenario, a couple of bars depicts the scores of technical and non-technical users for *easiness* and *time* dimensions.

6.5. Discussion

The formative evaluation was driven by the three research questions that we addressed by triangulating the collected qualitative and quantitative data. For RQ1, related to the users' ability to perform real co-located collaborative tasks by exploiting spatial awareness techniques, we observed that the participants were able to exploit the designed solutions in different co-located collaborative sensemaking scenarios. According to the questionnaire results, the participants appreciated the easiness and efficiency in executing the tasks required by the two scenarios. No difference emerged between technical and non-technical users. We also triangulated the quantitative questionnaire results with the qualitative data (open questions, video, audio) to better articulate our answer to RQ1. In particular, the four groups were able to complete the scenarios, even though some difficulties with the *Aggregation&Visualization* technique forced three groups to ask for help once. In order to improve users' awareness of the system status, in the next version of the system, a popup window shows a message that informs them that "the device is now part of a group. All the devices in the group can be queried together".

RQ2 addressed user satisfaction with performing co-located collaborative tasks using the proposed interaction techniques. The questionnaire results showed a high level of satisfaction. No difference was found between technical and non-technical users. Useful indications emerged on how to enhance further the three interaction techniques. For example, the proxy memorability could be improved by adding the logo/site name inside, as suggested by some participants. It is worth remarking that previous studies already investigated proxy usage for cross-device interaction as, for example, in [Rädle et al. 2015]. However, proxy memorability did not emerge as a problem in that study, probably because only simple tasks in a laboratory setting were performed, while we considered a more complex and real situation. According to these findings, the system was modified before performing the next comparative evaluation. A label inside the proxy indicates the site name visualized on the target device. The proxy size redoubles during the drag of UI elements, thus fostering an easier drop of large UI pieces inside the proxy. If two or more proxies are on the same line because of the physical position of the corresponding devices, they appear close instead of overlapping each other. Finally, the implementation of the Flying join technique was improved, in order to support the actions emerged in the formative evaluation. In particular, data items can be dragged from any source site onto the proxy of any target site.

About RQ3, i.e., if users would prefer different interaction techniques for the three composition operations, the participants provided some remarks only for the *Aggregation&Visualization* technique, because of the slight difficulties they experienced in realizing how to use it correctly. For example, some of them were hesitant on how to group different devices. Thus, there is room for improvements of this technique, which can be designed and evaluated in future work.

7. Comparative Evaluation

We carried out a comparative evaluation to assess if the three SACD techniques provide some advantages for the execution of collaborative sensemaking tasks in comparison with the use of mobile devices without any ad-hoc technique, which represents the state-of-the-art.

7.1. Participants and Study Design

A total of 27 participants (22 males, 5 females) were recruited among the students of the second and third year of Computer Science Bachelor degree courses at the University of Bari. The mean age was 23.33 years (SD = 1.96, min = 20, max = 28). The recruitment started 2 weeks before the study execution and it was performed by posting announcements on students' social networks and on the large displays located in different locations of the Computer Science department. One 8GB USB memory stick was offered as reward for participating in the study. They were randomly organized in 9 groups.

Two research questions guided the study:

RQ1) What is the difference in terms of user performance in accomplishing sensemaking tasks using mobile devices with and without SACD techniques?

RQ2) What is the difference in terms of user satisfaction in accomplishing sensemaking tasks using mobile devices with and without SACD techniques?

We performed a controlled experiment adopting a *within-subject design,* with *SACD* as independent variable and two within-subject conditions: *enabled* and *disabled*.

7.2. Tasks

The participants were required to interact with tablets to perform a set of tasks. As for the elicitation study, the proposed tasks were inspired to the data source composition and manipulation operations considered useful by end users of mashup tools, which are often used in sensemaking activities [Ardito et al. 2014b; Daniel and Matera 2014], i.e., *union* of data sources, *join* of data sources, and *data visualization.*

For each of these three operations, a task schema was designed (see Table 1). To achieve a higher internal validity, each schema was used to generate three tasks. To improve the external validity of the study, all the tasks required the use of popular Web sites and the achievement of simple but concrete goals.

Query a Device (QD) tasks ask to use a tablet running the Last.fm website to find a specific upcoming event in a UK city; a second tablet is used for searching in YouTube videos related to three singers listed in the Last.fm results. In the enabled condition, users interacting with Last.fm can use the *Flying Join* technique that allows them to drag the singers' name on the YouTube proxy, thus directly querying YouTube and visualizing the results on the second tablet. In the disabled condition, users can type on the YouTube tablet the singers' name to be used for the query.

Query a Group of Devices (QGD) tasks asked to query Zoopla, UK Air Pollution and Google Places Web sites running on three different tablets by using the name of a UK city. In the enabled condition, users can use the *Query Broadcasting* technique, by putting the devices close to each other for creating a group and then querying just one of them to automatically *broadcast* the same query to the other devices. In the disabled condition, users can type the given keyword in the Web site shown in each device.

Visualize an Item (VI) tasks asked to use a tablet to find in Zoopla the houses for rent in a UK city, and to use another tablet to show on Google Maps the position of three of them. In the enabled condition, by using the *Aggregation&Visualization* technique, the users can show the position of the Zoopla items on Google Maps and all at once. In the disabled condition, the user interacting with Google Maps can manually type each of the addresses communicated by the other user.

Table 1. The 3 experimental task schemas used in the comparative study. For each schema, to create three final tasks statements, *CITY* was replaced by an actual UK city name (namely, London, Liverpool and Manchester), while *I, J, K* were replaced by random numbers ranging from 1 to 20.

Task Schema	Task statement
QD	Use a tablet to search on Last.fm all the upcoming musical events in *CITY*. With a second tablet, open YouTube and search for videos using as keyword the name of the singer(s) you see at the *I*, *J* and *K* positions of the Last.fm results.
QGD	Use three tablets. On each of them open respectively Air Pollution, Zoopla e Google Places. Then, in each of these Web sites search data related to *CITY*.
VI	Use a tablet to search on Zoopla all properties for rent in CITY. Then, on a second tablet use Google Maps to locate the houses at I, J and K positions in the Zoopla results.

7.3. Procedure

The study took place in a quiet university room where the study apparatus was installed. Two HCI experts were involved: one acted as observer, the other as facilitator. Three tablets were adopted: a Samsung Galaxy Tab 3, a Lenovo TAB 2 A7 and an Apple iPad 3. To foster communications and interactions between participants, a rounded table was used [Buur and Soendergaard 2000] (see Figure 11). In the SACD techniques enabled condition, the HuddleLamp was activated.

The comparative study lasted 3 days. Three groups were individually observed each day. Every group followed the same procedure. First, they were introduced to the study purpose and what they had to accomplish. Participants were asked to sign a consent form. Nobody refused to participate in the study. The study procedure was preliminarily assessed by a pilot study involving two groups with six participants (three for each group).

The groups were provided with a booklet composed of two pages. Each page reported three training and nine experimental tasks to be performed in one of the experimental conditions. To avoid carry-over effect, the booklet pages were ordered to have the experimental condition order counterbalanced across the participants. In addition, the experimental task order on each page was counterbalanced across the experimental conditions, both according to a Latin Square design.

The facilitator introduced the first condition, i.e., the one reported on the first page of the participant booklet, and demonstrated how to perform one task for each of the task schemas. The demonstrated tasks were similar to the ones to be performed during the following training and experimental sessions. Then, the participants were invited to execute the three training tasks, possibly asking the facilitator for help.

After the training, the groups had to perform the experimental tasks. They had to read aloud the task text and then start the execution. At the end of all the experimental tasks, they filled in an online questionnaire. Before repeating the same procedure in the other condition, the participants were invited to relax for five minutes. Similarly to the formative evaluation procedure, the facilitator acted in a Wizard of Oz fashion [Dahlbäck et al. 1993] in order to alleviate the detection problems of HuddleLamp. At the end of the study, participants were asked to vote for their favourite condition.

Figure 11. Comparative study setting.

7.4. Data Collection

The evaluation addressed user performance and satisfaction in performing sensemaking tasks with and without the support of SACD techniques. Different types of data, both quantitative and qualitative, were collected. All the interactions were audio-video recorded by using an external camera. The observers took notes on significant behaviour or externalized comments. Online questionnaires were filled in during the study.

The two researchers transcribed their notes and performed an audio-video analysis of the records. As result, they built an excel file reporting for each task performed by each group the following data: group ID (from 1 to 9), condition (SACD techniques enabled/disabled), task ID (T1-T9), task type (QD, QGD, VI) and time (in seconds). Then, they independently double-checked such data. The initial reliability value was 94%, thus the researchers discussed the differences and reached a full agreement.

The online questionnaire included 28 questions. The first ten were the ones of the SUS questionnaire, and they were introduced to evaluate the overall system, without distinguishing the specific types of task. In the rest of the questionnaire, participants rated the three types of tasks by using the six subscales of the NASA TLX questionnaire, i.e., Mental demand, Physical Demand, Temporal Demand, Performance, Effort, Frustration (all subscales range from 0=low to 100=high) [Hart and Staveland 1988].

7.5. Performance Results

In order to answer the first research question, namely, if there is a difference in terms of *user performance* in accomplishing sensemaking tasks using mobile devices with and without SACD techniques, we analysed the time groups spent in performing the assigned tasks (see Figure 12).

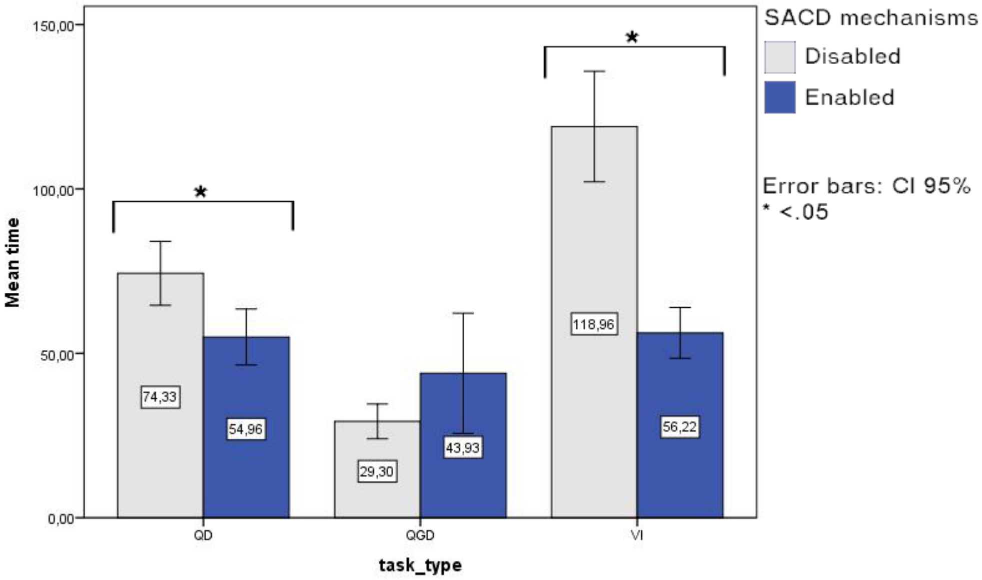

Figure 12. Bar chart showing the time groups spent in performing QD, QGD and VI tasks in both the conditions. The lowest mean time is the best.

For each type of task, paired-sample t-tests were adopted to find statistical differences in both conditions. The use of SACD techniques improve user performances in case of QD and VI tasks ($t_{QD}(26) = –3.436$, $p = .002$; $t_{VI}(26) = –6.946$, $p < .000$) while no differences emerged in case of QGD task ($t_{QGD}(26) = –1.654$, $p = .110$).

7.6. Satisfaction Results

In order to answer the second research question, namely, if there is a difference in terms of *user satisfaction* in accomplishing sensemaking tasks using mobile devices with and without SACD techniques, we analysed the questionnaire results. In order to obtain the overall user's satisfaction about each condition (i.e., SACD enabled vs. disabled), we analysed the answers of the first ten questions, which refer to the SUS questionnaire. For each participant, we calculated the SUS global score, as well as SUS learnability and SUS usability scores related to the two conditions [Lewis and Sauro 2009] (see Figure 13). For each SUS dimension, paired-sample t-tests were adopted to measure statistical differences between the two conditions. The SUS global score and SUS usability score were better in case of SACD enabled, while SUS learnability was better in case of SACD disabled ($t_{SUS}(26) = -3.072$, $p = .005$; $t_{lernability}(26) = 3.407$, $p = .002$; $t_{usability}(26) = -4.150$, $p < .000$).

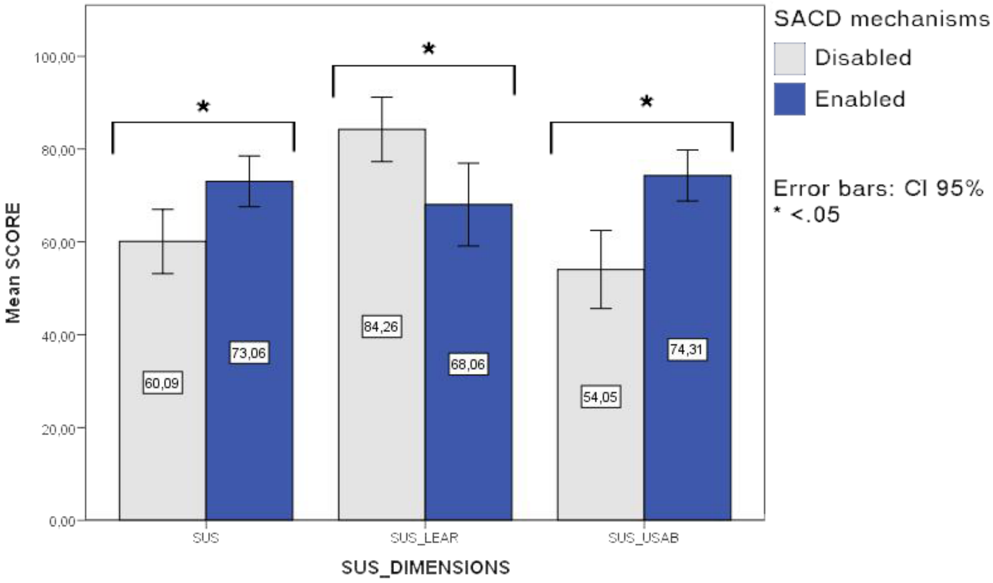

Figure 13. SUS score, SUS learnability and SUS usability of each condition.
The highest score is the best.

To better understand the user satisfaction with and without SACD techniques in relation to the type of task performed, we analyzed NASA TLX questions included in the second part of the questionnaires. The subjective ratings were analyzed with Wilcoxon Signed Rank Tests with a Bonferroni correction applied. In case of QD tasks, the use of the Flying Join technique was rated better in all the six dimensions, as summarized in the graph reported in Figure 14 ($Z_{effort} = -3.358$, $p = .001$; $Z_{frustration} = -3.632$, $p < .000$; $Z_{mental-effort} = -3.195$, $p = .001$; $Z_{performance} = -2.824$, $p = .005$; $Z_{physical-effort} = -4.077$, $p < .000$; $Z_{temporal-demand} = -3.832$, $p < .000$). In case of QGD tasks, the use of the Query Broadcasting technique was rated better only in frustration, physical effort and temporal demand dimensions, as summarized in the graph reported in Figure 15 ($Z_{effort} = -1.164$, $p = .244$; $Z_{frustration} = -2.640$, $p = .008$; $Z_{mental-effort} = -.442$, $p = .658$; $Z_{performance} = -1.118$, $p = .263$; $Z_{physical-effort} = -2.324$, $p = .020$; $Z_{temporal-demand} = -2.754$, $p = .006$). In case of VI, the use of the Aggregation&Visualization technique was rated better in all the six dimensions, as summarized in the graph reported in Figure 16 ($Z_{effort} = -3.604$, $p < .000$; $Z_{frustration} = -3.730$, $p < .000$; $Z_{mental-effort} = -2.960$, $p = .003$; $Z_{performance} = -2.636$, $p = .008$; $Z_{physical-effort} = -3.817$, $p < .000$; $Z_{temporal-demand} = -4.303$, $p < .000$).

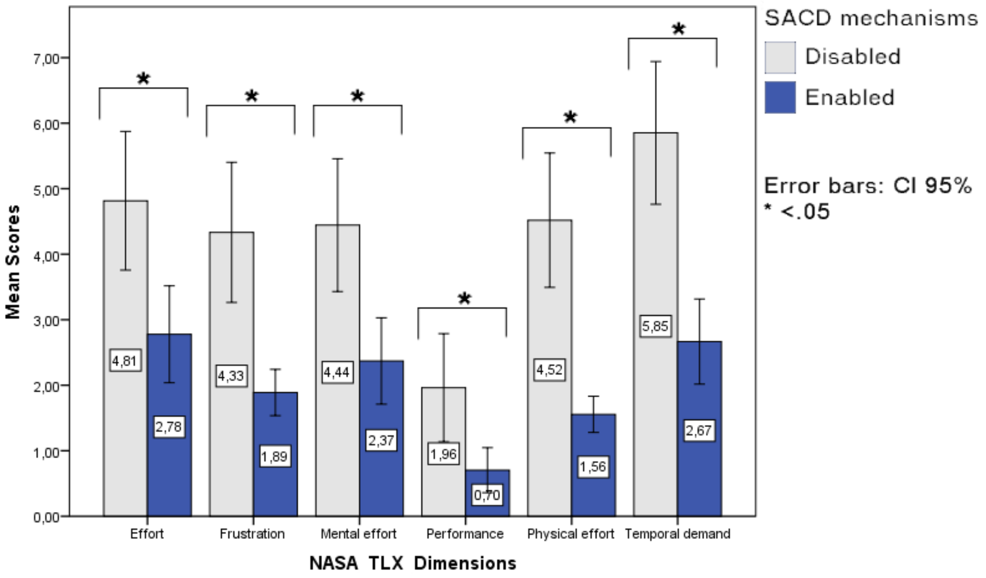

Figure 14. NASA TLX dimensions related to the QD tasks. The lowest score is the best.

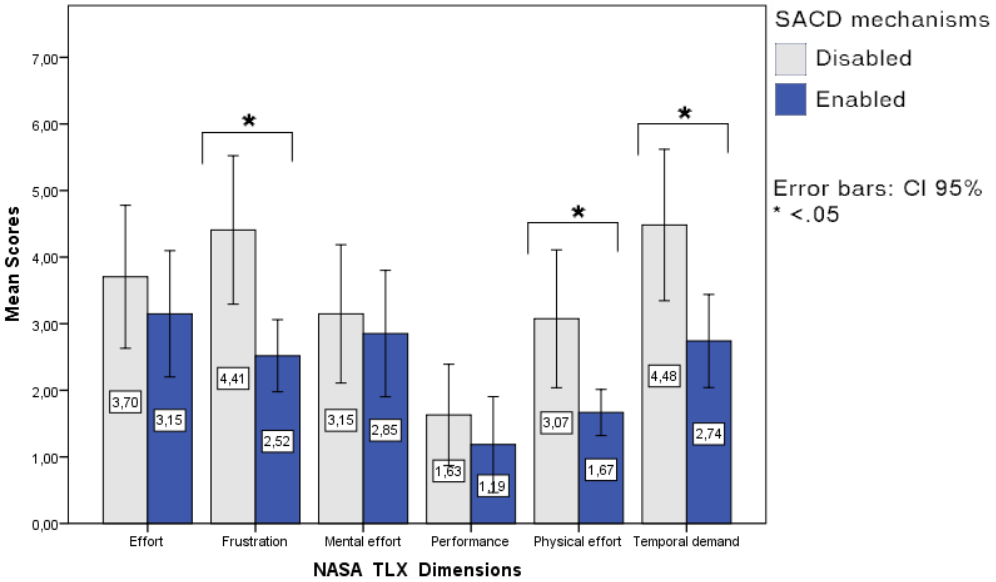

Figure 15. NASA TLX dimensions related to the QGD tasks. The lowest score is the best.

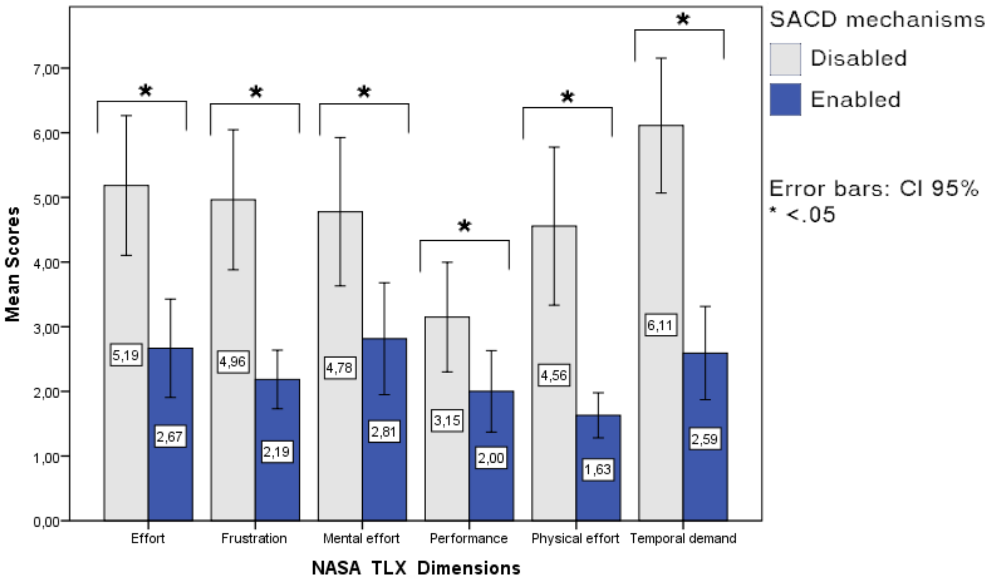

Figure 16. NASA TLX dimensions related to the VI tasks. The lowest score is the best.

7.7. Discussion

In terms of user performance, the *Flying Join* and *Aggregation&Visualization* techniques allowed the participants to perform sensemaking tasks faster than without any ad-hoc technique, while the *Query Broadcasting* technique did not provide any significant advantage. The analysis of the video recordings helped us to interpret these results. In case of QD tasks, groups acted faster using the *Flying Join* technique since it allowed them to perform the tasks by means of simple drag&drop actions. On the contrary, without the Flying Join, groups had to manually type the search keyword, e.g., the singer's name in the YouTube search field. In some cases, the participants also wasted time to verbally communicate among them the name spelling or to input again the search keywords due to a wrong verbal or written exchange of information. In case of VI tasks, groups acted faster thanks to the Aggregation&Visualization technique, since it allowed them to plot on Google Maps all the houses returned by Zoopla and to highlight on the map a specific house by simply tapping on the corresponding Zoopla item. On the contrary, without the Aggregation&Visualization technique, the participants had to manually type the entire address in the Google Maps search field. It also happened that, due to the address length, some participants wrote down the address on a paper sheet and gave it to the other participant who inserted it in Google Maps. In case of QGD tasks performed in the SACD technique disabled factor, the group members typed simultaneously the queries on each device, thus making their performance not significantly different from the SACD technique enabled condition. However, we deem that in a situation in which there are more tablets than users, the Query Broadcasting technique would provide a significant advantage in terms of performance for executing QGD.

Regarding the user satisfaction measured by means of the SUS questionnaire, the results revealed an overall participants' preference of systems with SACD techniques (see SUS global score in Figure 13). In addition, the decomposition of the SUS global score into SUS learnability and SUS usability scores revealed that, even if the SACD techniques have a good usability with respect to the use of the system without SACD techniques, they require more effort to be learnt (see in Figure 13 SUS usability score and SUS learnability score, respectively). A more detailed analysis of the users' preferences of each type of task was carried out according to the six dimensions: Mental demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. In case of QD and VI tasks, both the Flying Join and Aggregation&Visualization techniques were perceived as the best in all the dimensions, confirming the performances' results. Regarding the QGD, the Query Broadcasting was perceived better in frustration, physical effort and time dimensions, while no differences emerged in the other dimensions. Even if in the Query Broadcasting no difference emerged in terms of performances, the NASA TLX results confirm that users prefer this technique since it is perceived as faster, less frustrating and less tiring.

Summing up, we performed a comparative study to investigate if users' ability in performing sensemaking tasks [Dervin 1983] can be supported by using novel SACD techniques or traditional solutions. On the light of the evaluation results, we can assume that SACD techniques help group of people in performing co-located sensemaking tasks better than traditional mobile interaction mechanisms. Indeed, performance results revealed that users were able to bring down to workable time to complete a task. In addition, user satisfaction results, in particular mental effort measured thanks to NASA-TLX, highlighted that user's memory demand gets lower by using SACD techniques, thus increasing reliability and number of jobs handled at once [Kirsh 1995].

7.8. Threat to Validity

In this section, we analyse some issues that may have threatened the validity of the comparative evaluation, also to highlight under which conditions the study design offers benefits that can be exploited in other contexts, and under which circumstances it might fail.

7.8.1. Internal validity

Internal validity can be threatened by some hidden factors compromising the achieved conclusions:

- *Learning effect*. In our experiment, this factor was minimized by counterbalancing the conditions (SACD techniques *enabled* and *disabled*) and the experimental tasks order across the conditions, both according to a Latin Square design.
- *Subject sample appropriateness.* As discussed in [Ko et al. 2015], "the recruiting phase represents one of the most critical steps of the experiments because good inclusion criteria have to reflect the characteristics of the users that researchers believe would benefit from using the experimented tools" and "students can be appropriate participants when their knowledge, skills, and experiences fit within a tool's intended user population". Since the recruited participants were young students, we can safely assume that the study participants represent a significant portion of targeted end users. However, we cannot generalize our results to the entire target of users.
- *Subject experience*. It was alleviated by the fact that none of the subjects had any experience with the experimented systems.
- *Method authorship*. We eliminated the biases that different facilitators running the experiment could introduce, as we had the same instructor for every session of the study. In this way, we avoided any variability in the initial training as well as in the way users had been observed.
- *Information exchange*. Since the study took place over 3 days, it is difficult to be certain whether the involved subjects did not exchange any information. However, the participants were recruited from different classes and during exams period thus, for many of them, it was difficult to know each other and to communicate. The participants were asked to return all the material (e.g., the booklet) at the end of each session. We asked participants coming from the same classes and who typically study and travel together to perform the test in the same session.
- *Understandability of the material*. A pilot study involving two groups with six participants (three for each group) was carried out to assess the understandability of experimental procedures and materials.

7.8.2. External validity

External validity refers to the possible approximation of truth of conclusions in the attempt to generalize the results of the study in different contexts. With this respect, the main threats of our study are:

- *Participants' age.* Since the study participants were young students, we have to take into account the participants' age that limits the prediction of the benefits of the tools to older people. Thus, we can safely accept the experiment results for digital natives [Prensky 2001], but further studies have to be carried out including older people.
- *Comparison with other tools.* In the comparison, we considered only the same system without SACD techniques. Even if, as reported in Section 2.2, further spatial aware and/or cross-device systems are available, they were not included in the study for two reasons: 1) all of them are research tools not available as open source systems and 2) they are very different from the one we propose.

7.8.3. Construct validity

Construct validity might have been influenced by the measures we adopted in the quantitative analysis and by the reliability of the questionnaire. We alleviated the first threat by adopting measures, such as efficiency (e.g., time to complete a task), that are commonly employed in user studies [Dix et al. 2003].

7.8.4. Conclusion validity

Conclusion validity refers to the validity of the statistical tests applied. In our comparative study, this was alleviated by applying the most common tests that are employed in the empirical software engineering field [Juristo and Moreno 2013].

8. Recurring Themes and their Implications for Design and Future Research

From our elicitation study, we gathered a wealth of specific suggestions for cross-device interactions. We also learned how well our specific design manifestations of these suggestions performed during the two follow-up evaluations. However, there were also more fundamental and far-reaching themes that were repeatedly brought up by participants or occurred during the studies. In the following, we summarize these observations that go beyond our specific design under two themes and discuss their implications for design and future research.

8.1. Ambiguity of Proximity: From proximity to proxemics

Previous work has documented how space helps users work with objects that cannot be clearly categorized or filed yet and for which it is unclear how they will be used [Kidd 1994]. In such cases, users often use proximity to informally cluster related objects in piles or heaps at different locations in space. This strategy of informal *piling* leaves potentially helpful objects visible and accessible and simplifies perception and choice [Kirsh 1995]. The spatial layout of objects also gives them powerful and immediate contextual cues that serve as a representation of the users' context and activities. For example, spatial configurations can help users to recover a complex set of threads without difficulty and delay after interruptions [Kidd 1994] or they can help to raise group awareness during collaborative sensemaking [Jetter et al. 2011]. Arranging virtual or physical objects in space during knowledge work and sensemaking is therefore frequently observed for virtual desktops [Ravasio and Tscherter 2007], large interactive screens [Andrews et al. 2010], as well as physical office desks [Kidd 1994; Malone 1983].

Therefore, while it seems very natural to users to express similarity or connectedness between objects or devices by moving them close together, this does not necessarily tell us about the precise nature of this similarity or connection. Proximity alone lacks the expressiveness to qualify the kind of relation, e.g., if two devices should serve as two data sources whose output is merged, or if one should serve as data sink and visualization for the other data source. This problem became obvious in the many conflicts and inconsistencies in the proposed interactions of the participants during the elicitation study and formative evaluation. Moving two objects closer together or side-by-side did not have an unambiguous meaning, but participants assigned it with different meanings depending on the context and task at hand. What they wanted to express by decreasing or increasing the physical distance between objects was therefore highly context-dependent and could not be mapped to a system function in a straightforward manner.

Although our spatially-aware techniques already proved to be more efficient in our comparative evaluation, designers and the systems they build should take into account the full richness of *proxemics* [Greenberg et al. 2011] and their dimensions which go far beyond simple *distance* but also include *location*, *orientation*, *movement*, and *identity* of devices. While we focused primarily on location and distance, future systems could especially explore the use of orientation, movement and identity of both users and devices to a greater extent.

Another approach could be to enable users to precisely define the nature of a spatial relation in a two-step interaction: First, the users move devices closer together or further away to indicate which devices should be involved (i.e., selecting OBJECTS) as well as the strength of their relationship by using distance as an implicit expression of connectedness (i.e., selecting STRENGTH). In a second step, users could be asked to specify the kind of relationship they want to express, for example, by explicitly selecting one of different types of relations from a popup menu (i.e., selecting RELATION). Alternatively, different orientations of devices could also be used to express the direction of the relation, e.g., in which direction data flows. By this, similar to the OBJECT-ACTION syntax of context menus in desktop operating systems, this kind of OBJECTS-STRENGTH-RELATION syntax could introduce spatial interaction techniques to let users explicitly control the type of relationship when proximity alone is too ambiguous.

8.2. Multi-Modal Referential Domains: Easier selection of remote devices

A very frequent task during cross-device interaction is interacting with one device to exchange content or settings with another remote device, e.g., moving an object from a source tablet in your hands to a destination tablet that is lying on a table a few meters away or is held by another user somewhere else in the room. Such tasks make it necessary to precisely and quickly select a remote device with an effective and efficient interaction technique that does not demand too many cognitive resources. For example, selecting a remote device simply by pointing at it with a finger might be much more usable and less time consuming than remembering and entering a long alphanumeric string as device identifier.

In their taxonomy of cross-display movement techniques, Nacenta et al. introduce the term “referential domain” for “the different methods or ‘languages’ in which objects can be referred to” [Nacenta et al. 2009]. They classify referential domains into two groups, spatial and non-spatial. A technique is spatial if it references devices spatially, i.e., if the required input to select a device relates in a spatial way to the position of the display in the physical arrangement of devices (e.g., pointing a gesture to a device). A technique is non-spatial when the destination device is referenced in any way that is not spatial, e.g., through names, through the navigation of hierarchies, through lists, through association with colours or shapes [Nacenta et al. 2009].

Recent research has found that using the spatial domain can be very successful. For example, Rädle et al. found that their spatial “edge bubbles” technique that combines spatial techniques with colour coding was superior to techniques that relied on colour coding alone [Rädle et al. 2015]. However, a hybrid “radar view” showing a color-coded top-down view or map of all devices, did not show the same performance, revealing that the way in which spatiality is introduced must be chosen carefully.

Despite the advantages of the “edge bubbles” we adopted and revised for our Flying Join technique, our studies highlighted room for improving its performance. First, “edge bubbles” introduce a cognitive overloading because users have to memorize the mapping between device colours and bubble colours. This problem did not emerge when users were required to use “edge bubbles” for simple laboratory tasks involving few devices [Rädle et al. 2015]. On the contrary, in more complex and real tasks, like the ones of our formative evaluation where 4/5 devices were involved, participants demonstrated a significant mental effort. Another limitation regards the proxies size. In fact, since mobile devices have a display size ranging from 7 to 11 inches, proxies have a size like a fingertip in order not to cover other UI elements. Thus, it can be very difficult to drop large UI elements inside a proxy; this difficulty was indeed experienced by our participants during the formative evaluation, when they tried to drop pieces of text inside the proxies. The last limitation regards the proxies overlapping: since the bubble locations are defined by imaginary lines connecting the central point of the source device and the central point of the target devices, if two or more devices are on the same imaginary line their proxies are overlapped.

From the observations of the user behaviour during our studies and from the analysis of the user comments, we derived the following suggestions for the design of hybrid multi-modal referential domains. First, regarding the proxy memorability, in order to decrease the user mental effort, a label inside a proxy should indicate the target device, for example the site name or site logo. Second, regarding the proxy size problem, we suggest doubling the proxy size only during the drag of UI elements, thus facilitating the drop of large UI pieces inside the proxy. Third, regarding the proxies overlapping, during the drag of UI elements inside a proxy, if two or more proxies are on the same line, they should appear close instead of overlapping.

9. Conclusion

In this article, we have proposed a data composition paradigm consisting of a set of spatial-aware cross-device techniques for supporting users in performing sensemaking collaborative tasks. The paradigm has been conceived and preliminary assessed on the basis of a three-step research study. First, we carried out an elicitation study in which we stimulated users to perform, by means of touch gestures and/or arrangement of devices on a desk, some data composition operations typical of sensemaking collaborative tasks. Then, a formative evaluation allowed us to carry out a preliminary assessment and to refine the composition paradigm. Finally, a comparative study was performed to evaluate if the SACD paradigm has an impact on the execution of sensemaking collaborative tasks. The study results are encouraging: 1) the proposed techniques support group of people in performing co-located sensemaking tasks better than the state-of-the-art mobile interaction mechanisms; 2) the participants were able to complete the tasks in less time, with less mental effort and with more satisfaction, also increasing reliability and number of jobs handled at once.

Even if these techniques enable the execution of a wide range of data operations useful in sensemaking scenarios, we are aware that other operations can be considered. However, at this stage of our research, we aimed to consolidate a ground of techniques covering the most important and frequent data manipulation tasks. We are currently working to extend our paradigm by designing techniques for operations like selecting, filtering, sorting. We are also working on how to extend the composition paradigm out of the 2D physical space, thus allowing users to perform sensemaking tasks in 3D space. This extension poses some challenges. For example, how users group devices together? The desk could become the space where users establish connections among their devices and later they can freely move in the environment and perform their collaborative activities supported by SACD techniques. Furthermore, SACD techniques suitable for a 3D setting have to be defined, possibly considering a technique recently presented in [Dingler et al. 2018] to design cross device gestures and techniques.

We are also investigating how to extend the proposed approach in order to involve different types of devices. As illustrated in the Related Work section, different solutions have been already proposed to support interaction across devices like smartwatches, PCs, large displays. In the era of ubiquitous computing, providing a seamless user experience is crucial, because of the growing availability of different devices. At the current state, the solution described in this paper supports only tablets and smartphone, but we are confident that there is still room for improvements in term of types of device involved. To this aim, we are considering new strategies to both synchronize different device types and design new SACD techniques that are adequate to perform sensemaking tasks [Dingler et al. 2018].

Investigating the social aspects of system providing SACD mechanisms is another aspect to be considered as future work. For example, determining if there is an influence on the group's verbal communications during the interaction is a factor to consider when designing the SACD mechanisms. During the study, we observed that groups interacting without SACD techniques were forced to tedious, time-consuming and error-prone verbal or written exchange of information about performed queries and retrieved results. On the contrary, SACD techniques assisted users in reducing useless verbal communication and allowed them to be focused on the goal of the sensemaking tasks. Observing which kind of useless communications occur when using SACD techniques and which of them can be still reduced, we can refine the current SACD techniques and we can identify design indications to create optimized cross-device mechanisms that better support sensemaking tasks.

Finally, we are aware that the current implementation suffers from the limitations of the adopted HuddleLamp technology, i.e., detecting and tracking failures, the number of the devices on the desk and the need of laying them down on the table. Nevertheless, at the current stage, the main goal was defining a set of composition techniques, to enable sensemaking activities by combining and interacting with spatial-aware mobile devices. However, we are working to improve the technical limitations in order to adopt the system in real contexts. A technological improvement will allow us to perform field studies and longitudinal studies to assess the advantages of the data composition paradigm when adopted in real contexts and to better understand which type of tasks and scenarios can be supported.

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