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Querytogether: Enabling entity-centric exploration in multi-device collaborative search

Salvatore Andolina*,[a], Khalil Klouche[b], Tuukka Ruotsalo[b], Patrik Floréen[b], Giulio Jacucci[b]

[a] *Helsinki Institute for Information Technology HIIT, Department of Computer Science, Aalto University, Finland*
[b] *Helsinki Institute for Information Technology HIIT, Department of Computer Science, University of Helsinki, Finland*

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ABSTRACT

Collaborative and co-located information access is becoming increasingly common. However, fairly little attention has been devoted to the design of ubiquitous computing approaches for spontaneous exploration of large information spaces enabling co-located collaboration. We investigate whether an entity-based user interface provides a solution to support co-located search on heterogeneous devices. We present the design and implementation of QueryTogether, a multi-device collaborative search tool through which entities such as people, documents, and keywords can be used to compose queries that can be shared to a public screen or specific users with easy touch enabled interaction. We conducted mixed-methods user experiments with twenty seven participants (nine groups of three people), to compare the collaborative search with QueryTogether to a baseline adopting established search and collaboration interfaces. Results show that QueryTogether led to more balanced contribution and search engagement. While the overall s-recall in search was similar, in the QueryTogether condition participants found most of the relevant results earlier in the tasks, and for more than half of the queries avoided text entry by manipulating recommended entities. The video analysis demonstrated a more consistent common ground through increased attention to the common screen, and more transitions between collaboration styles. Therefore, this provided a better fit for the spontaneity of ubiquitous scenarios. QueryTogether and the corresponding study demonstrate the importance of entity based interfaces to improve collaboration by facilitating balanced participation, flexibility of collaboration styles and social processing of search entities across conversation and devices. The findings promote a vision of collaborative search support in spontaneous and ubiquitous multi-device settings, and better linking of conversation objects to searchable entities.

1. Introduction

The impact of search on our everyday lives is unparalleled. Yet, surprisingly, search is often thought of as a solitary user activity, focusing on eliciting a user's information needs and improving search-result relevance. Recently, increasing attention has been devoted to search as a collaborative activity that is often co-located, spontaneous and initiated informally from a dialogue (Brown, McGregor, & McMillan, 2015; Morris, Fisher, & Wigdor, 2010a). Users are inspired or informed by others' searches, and can distribute search efforts, exploring the information space in parallel. Despite the increasing number of situations in which several co-located people engage in collaborative search, available devices and public screens are not effectively used for synchronous collaboration.

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* Corresponding author.
E-mail address: salvatore.andolina@aalto.fi (S. Andolina).

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Situations addressed by existing collaborative search systems include distributed users on mobile interfaces, or co-located interaction on tabletops. We wanted to focus on a common ubiquitous computing scenario in which several co-located users spontaneously engage in collaborative search, using personal devices as well as available large screens or projectors. In particular, we investigate what user interfaces and search systems facilitate collaboration across such devices.

Several collaborative search systems have been proposed (Table 1), supporting either distributed collaboration (Halvey, Vallet, Hannah, Feng, & Jose, 2010; Morris & Horvitz, 2007; Paul & Morris, 2009; Wiltse & Nichols, 2009), or co-located search situations (Amershi & Morris, 2008; Chung, North, Self, Chu, & Quek, 2014; Golovchinsky, Adcock, Pickens, Qvarfordt, & Back, 2008; Jetter, Gerken, Zöllner, Reiterer, & Milic-Frayling, 2011; Morris, Lombardo, & Wigdor, 2010b; Morris, Paepcke, & Winograd, 2006; Teevan, Morris, & Azenkot, 2014). Collaborative search systems have targeted different kind of devices and their typical features include support for result sharing and coordination of work. Moreover, methods and tools supporting these activities continue to be general-purpose communication systems, such as email or instant-messaging systems (Morris, 2008) or, in co-located situations, face-to-face communication. Conversely, support for exploratory search in collaborative situations has remained largely unaddressed (Hearst, 2014). We maintain that the problem of ubiquitous co-located search should be targeted as a new design problem that considers a range of devices, including smartphones, tablets, laptops, and larger public screens utilized simultaneously in the same environment. In this context, user interface concepts need to consider the opportunities provided by multitouch interaction in manipulating information directly as well as constraints, such as the limited possibility of text entry on different devices.

The main research question that we investigate is whether an entity-based user interface (Klouche et al., 2015) provides a solution to support co-located search on heterogeneous devices. Such interfaces have only been investigated in search systems tailored to individual users, especially to facilitate exploration on touch devices without a physical keyboard. How they affect collaborative search is still unknown. Entity search, recently adopted in Web-wide knowledge graphs, is an opportunity to move search from keyword-based text queries on unstructured data, toward semantic search that recognizes how text refers to different types of things, such as people, places, organizations, etc. Similarly, a user interface that allows queries and results to be formulated using entities provides information that can be manipulated in an intuitive way and might be better suited for mediated interaction between people. Recent studies on collaborative search demonstrate how it is often co-located, spontaneous and initiated informally from a dialogue (Brown et al., 2015; Morris et al., 2010a), such that search should integrate with the conversational context identifying "searchable objects." Ideally, in the future, any entity mentioned in a conversation will be searchable (Andolina et al., 2018; Brown et al., 2015; Shiga, Joho, Blanco, Trippas, & Sanderson, 2017). While the query-and-response paradigm, with long lists of document-based results, works well for individual look up search, it falls short in exploratory and mobile scenarios (Klouche et al., 2015). As in the latter cases, we posit that entity-based interfaces effectively support collaborative search in ubiquitous settings. We start by analyzing the state of the art of collaborative search situations and tools to understand current trends and needs in collaborative search and devise general design goals for our system.

We present the design and implementation of QueryTogether (Fig. 1), a collaborative search system designed for co-located exploratory search in which two or more physically co-located users search together supported by entity-centric recommendations. QueryTogether was deployed in a multi-device collaborative environment with tablets and large screens, and evaluated in a collaborative exploratory search study with nine groups, each consisting of three people. Conventional laptops and large screens, with more traditional search tools based on queries and lists were used as a baseline for comparison. The study's goal was to evaluate QueryTogether and understand how its novel design, including explicit support of exploration through entity-centric recommendations, affects collaborative search in terms of exploration support, collaboration, and engagement. The results show that, relative to the baseline, QueryTogether leads to significantly improved contribution balance and search engagement without compromising effectiveness. Interaction analyses also suggest that QueryTogether led to more effective usage of the heterogeneous devices together with improved support for diverse collaboration styles and common ground establishment.

2. Background

Collaborative search is increasingly documented as an activity that initiates spontaneously as part of co-located social interactions (Brown et al., 2015; Morris et al., 2010a). Informal opportunistic interactions among colleagues, for example, often happen by chance in common areas or cafeterias, and they may lead to conversations that end up being critical to a project's success (Isaacs, Tang, & Morris, 1996; Kraut & Streeter, 1995). As part of such conversations, people may spontaneously turn to their personal devices to collaborative search for information (Brown et al., 2015) that may or may not be familiar (Hearst, 2014). However, the systems designed to support collaborative search, until now, have focused mainly on increasing awareness of search activity and division of labor across collaborators (Morris & Horvitz, 2007; Zhang et al., 2017), leaving other important aspects of collaborative search less investigated.

Table 1 summarizes several attempts to create collaborative-search support varying from conventional distributed Web-search extensions to domain-specific tabletop designs. SearchTogether (Morris & Horvitz, 2007) facilitates remote collaboration by supporting awareness, division of labor, and persistence. ViGOR (Halvey et al., 2010) uses similar principles but in the multimedia domain. MUSE (Krishnappa, 2005) allows pairs of remote users to search for medical information. CoSense (Paul & Morris, 2009) supports remote collaborative search by focusing on sense-making and providing several rich, interactive views of users' search activities. CollabSearch (Yue, Han, He, & Jiang, 2014) is a Web search system where collaborators can save Web pages or snippets and make comments. Similarly, Coagmento (Shah, 2010) provides integrated support for communication, note-taking, and the collection of text snippets or other objects from Webpages. ResultSpace (Capra et al., 2012) provides awareness of the group activity by displaying query histories. It also supports the rating of query results and includes filtering controls based on ratings from

Table 1
Comparison of different collaborative search interfaces.

	Activity Supported	Division of Work	Sharing Mechanisms	Exploratory Support	Spatial Configuration	Devices
SearchTogether (Morris & Horvitz, 2007)	Web search	Split and multi-engine search	Query awareness and messaging	–	Distributed	Desktop
CoSense (Paul & Morris, 2009)	Web search	–	Awareness views	–	Distributed	Desktop
CoSearch (Amershi & Morris, 2008)	Web search	–	Multiple cursors on screen	–	Co-located	Desktop and mobile
WeSearch (Morris et al., 2010b)	Web search	–	Sharing results snippets	–	Co-located	Tabletop
VisPorter (Chung et al., 2014)	Text analytics	–	Push to shared display	–	Co-located	Personal device and shared screen
PlayByPlay (Wiltse & Nichols, 2009)	Web browsing	–	Send my actions	–	Distributed	Desktop and mobile
O-SNAP (Teevan et al., 2014)	Restaurant search	–	Change device orientation	–	Co-located	Mobile devices
CollabSearch (Yue et al., 2014)	Academic search/travel planning	–	Share snippets and webpages	–	Distributed	(Not specified)
Coagmento (Shah, 2010)	Web search	–	Share snippets of information	–	Distributed	Desktop
Result Space (Capra et al., 2012)	News articles search	–	Query histories	–	Distributed	Desktop
TeamSearch (Morris et al., 2006)	Image search	–	–	Faceted search	Co-located	Tabletop
Facet-Streams (Jetter et al., 2011)	Hotel search	–	–	Faceted search	Co-located	Tabletop
Cerchiamo (Golovchinsky et al., 2008)	Video retrieval (Pickens et al., 2008)	Pre-defined roles	–	Algorithmic mediation	Co-located	Shared display
Querium (Golovchinsky et al., 2012)	Scientific literature search	–	Share documents and queries	Algorithmic mediation	(Not specified)	(Not specified)
QueryTogether	Scientific literature search	–	Push entities publicly to shared display or privately to peer	Entity centric exploration	Co-located	Tablets, laptops, and large screens

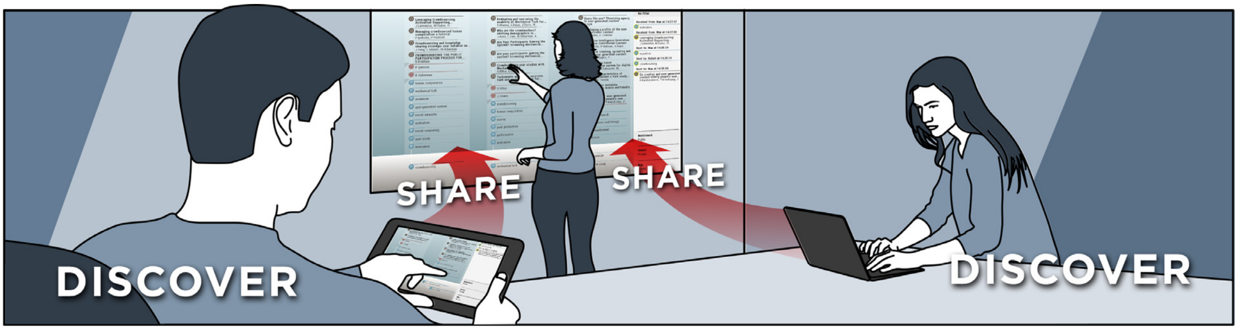


Fig. 1. QueryTogether. The system enables multi-device co-located collaboration for search. It explicitly supports exploration by providing entity-based recommendations to group members. The system supports diverse collaboration styles, ranging from individual work to tight collaboration. Each group member can search privately and share interesting results or search cues either privately with individual teammates or publicly with the whole group.

individual collaborators. CoSearch (Amershi & Morris, 2008) is designed for enhancing collaborative Web search in a shared-computer setting, by leveraging multiple mice and mobile devices. The design space of using tabletops for collaborative Web search systems has been explored with several systems: TeamSearch, FourBySix Search, Cambiera, and WeSearch (Morris et al., 2010a; Morris et al., 2010b).

Two particular aspects remain poorly investigated in related research: support for collaborative exploration (Hearst, 2014), and the co-located use of heterogeneous devices. First, we review insights originating from earlier research on collaborative searches with a special focus on support for exploration. Then, we analyze how previous approaches have considered the diversity of devices and setups. Finally, we introduce the notion of entity to the context of semantic computing and delve into how it can be incorporated into novel exploratory search systems. We end by summarizing the answers to the research questions posed by this work.

2.1. *Collaborative exploratory search*

According to a survey on 150 users conducted by Evans and Chi (2010), most people (around 59%) engage in collaborative searches as part of an exploratory process of searching for information that may or may not be familiar. Exploratory search (Marchionini, 2006) refers to complex search tasks in which users' understanding of information needs, and the information available in the data collection, can evolve during the search session. Traditional search systems tailored for well-defined narrow search tasks may lack the necessary support for exploratory search where users can sequentially refine the expression(s) of their information needs and explore alternative search directions. Although, at the individual level, a large body of work targeting exploratory search has been produced in the last decade, surprisingly, specific features for supporting exploratory search are often been missing from collaborative search systems.

In the context of individual search, there have been many examples of techniques and systems that support exploratory information needs. Researchers in the area of semantic web have proposed several strategies to address the need for exploration in search, mainly relying on different kinds of classifications (see Wilson, Kules, schraefel, & Shneiderman, 2010 for a review). Other strategies include the use of interactive intent models that enable refining of the current search intent and identifying search directions (Ruotsalo, Jacucci, Myllymäki, & Kaski, 2014). Other approaches mainly focus on supporting exploration at the interface level, such as TweetBubble (Jain et al., 2015), which extended the Twitter interface to stimulate exploratory browsing of social media. A novel approach is the one introduced by ExplorationWall (Klouche et al., 2015), a system aimed at supporting exploration at both the interface and the system level by coupling an entity-centric recommendation engine with a novel visual interface based on parallel search streams. Unfortunately, these strategies and systems have only targeted single user scenarios.

In collaborative search situations, the main strategy for handling the need for exploration has been to rely on collaboration itself. Current systems have thus focused on enabling features to improve the collaborative process, such as awareness of other team members, communication, and division of work. However, specific features for supporting exploratory search, such as those proposed for individual users, are often missing. Although not specifically designed for exploration, TeamSearch (Morris et al., 2006) and Facet-Streams (Jetter et al., 2011) may support exploratory information needs, to some extent, by leveraging faceted search (Yee, Swearingen, Li, & Hearst, 2003). With faceted navigation, users can narrow search results by incrementally applying multiple filters, called facets (Tunkelang, 2009). Available facets (either existing categories or computed through clustering) provide an overview of the information space allowing users to choose from a list instead of coming up with a query. The exploration, however, is limited since faceted search typically relies on Boolean filters to determine a list of equally relevant items that are then sorted according to an arbitrary criterion (e.g., time, price). Moreover, such a binary approach to relevance creates limited opportunity for discovery and insights. Our approach obviates this problem by allowing the users to express preferences on entities that they find useful, presenting results sorted according to relevance estimation, without excluding information based on arbitrary criteria. Cerchiamo (Golovchinsky et al., 2008) uses a different approach by providing support for exploration in an implicit way, namely through algorithmic mediation (Pickens, Golovchinsky, Shah, Qvarfordt, & Back, 2008) and by introducing roles. Cerchiamo avoided explicit sharing and focused on ensuring that the search results of individual users would automatically be influenced by the group's search process. One limitation to this approach is that users do not have any control on what information is shared. Also, this approach only supported a form of loosely coupled collaboration, while it lacked support for tightly coupled collaboration. In a similar way, Querium (Golovchinsky, Dunnigan, & Diriye, 2012) supports exploration through system mediation. However, unlike Cerchiamo, Querium also provides communication and sharing features to enable more tightly coupled collaboration.

Our system, QueryTogether, is unique insofar as it provides support for exploration at both the interface and the system level. At the interface level, QueryTogether supports exploration through the novel representation of entities as interactive searchable objects, whereas at the system level provides smart entity recommendations for directing future searches. In this way, QueryTogether leaves control to the users who can transition between phases of loosely and tightly coupled collaboration as needed. In QueryTogether, the feature of entity-centric exploration, which has proved to be effective for individual users (Klouche et al., 2015), is adapted to a collaborative-search setup.

2.2. Multi-device search

Although collaborative search has mainly been envisioned as taking place around a single shared device (Morris et al., 2010a; Morris et al., 2010b), recent research has pointed out the importance of enabling users to initiate their searches at any time or place and with any available device based on how their information needs are triggered (Han, Yue, & He, 2015). A study conducted by Brown et al. (2015) further showed the importance of supporting mobile collaborative search at any time. Their results revealed how collaborative mobile-phone search often happens as part of informal conversations, and how searchers manage the participation of other interlocutors alongside the search itself (Brown et al., 2015).

Some collaborative systems have attempted to support multi-device interaction in search. CoSearch (Amershi & Morris, 2008), for example, supports co-located collaborative search through a shared display and multiple input devices, such as extra mice or mobile phones. Mobile phones allow individual searchers to control several functions on the shared display and to download Web pages from the shared display to their private mobile devices, thus enabling individuals to read the same Web page at their own pace. Although CoSearch provides users with more control and independence than a traditional shared interface can, the independence provided is still limited. For example, all collaborators can suggest search terms, but only the "driver" of the shared interface can execute queries.

PlayByPlay, Wiltse and Nichols (2009) supports remote collaborative search between mobile and desktop users in on-the-go scenarios by using an instant-messaging channel that allows users to send snippets of Web content. An informal study on a simulated mobile search scenario showed that the slowness of text entry was generally a problem that needed to be addressed. In the present study, however, we do not focus on remote collaboration but rather on collaborative search situations where users are physically co-located. O-SNAP, Teevan et al. (2014) proposes a multi-device mobile scenario for co-located restaurant search. The system supports the switch between individual and group search using phone orientation: vertical orientation was used for individual search, while landscape orientation was used to enter collaborative mode and have the application state of an individual (including search terms, result list, and current view) propagated across all other devices in the mode. This approach, however, posed coordination challenges when multiple users tried to control the screens at once.

In contrast to those systems, QueryTogether enables collaborative search on a wider variety of devices, including tablets, laptops and large touchscreens. This is achieved through a responsive design featuring a mechanism for typing-free querying via direct manipulation of search entities, which is particularly suitable for interaction on small-screen devices but also applies well for searching on larger screens. Unlike systems such as CoSearch, which offer limited features on smaller devices, QueryTogether provides the same set of features on all available devices. Other systems, such as VisPorter (Chung et al., 2014), support collaboration and the sharing of resources on a large variety of devices. They do not support collaborative search, but they do promote collaborative sense-making. Another difference with respect to other multi-device systems is that QueryTogether allows some devices to be used in public mode as shared workspaces, and the rest of devices in private mode for which individuals have full control over what they want to share. In this way, QueryTogether maintains the advantages of both early collaborative search systems implemented on shared tabletops and more recent systems supporting phases of independent search, such as PlayByPlay and O-SNAP.

2.3. Entity-based search interfaces

Traditional methods of information access have used a keyword-based query and a document-based response. The limited and well-defined scope of this paradigm works well in terms of addressing user intents in familiar search contexts. However, it is inefficient for complex tasks and does not allow for the efficient modeling of complex user intents in the information space (Ruotsalo et al., 2014).

Entity-based systems provide users with named entities (e.g., people, places, topics) to better address specific information needs. Conventional search engines often use Wikipedia as a comprehensive entity collection, in an entity-recommendation approach, to answer entity-centric queries. Yet, despite how comprehensive Wikipedia content may seem, most relevant information (e.g., very recent news events) is usually presented in natural language and not structured and linked according to standards.

Researchers in the fields of semantic computing and information retrieval are investigating new approaches to overcome such limitations (Balog, Meij, & de Rijke, 2010). In particular, the goal of semantic computing is to understand the naturally expressed intentions of users, determine the semantics and express them in a machine-processable format. In addition, armed with the ability to model and express users' intentions, it models and processes content and information, inferring meaning and therefore its semantics. In this way, it makes it possible to map the semantics of the user with the semantics of the content, allowing users to share meaning

(Hasida, 2007).

Recently, Web-scale knowledge graphs demonstrate through recent advances in open-information extraction (OIE) how to structure and semantically link entities from information extracted from the Web (e.g., Freebase, DBPedia, Google Knowledge Graph, Knowledge Vault (Dong et al., 2014)). Several exploratory search systems have been developed around such efforts. Some systems rely mostly on the visualization of the entity graph as provided by the database to provide links to Wikipedia articles (Nuzzolese et al., 2017). Others use interactive visualization and retrieval algorithms to rank meaningful results (Castano, Ferrara, & Montanelli, 2014; Marie, Gandon, Ribière, & Rodio, 2013).

In most cases, results are still document based, with an entity-based interactive visualization on the side. Recent entity-based systems supporting exploratory search use entities both in the results and as a query, with documents considered just another type of entity (Andolina et al., 2015; Klouche et al., 2015). Such design allows each result to be used as the start of a new search, thereby respecting the iterative and open-ended nature of exploration. When visualized as interactive objects, entities make for flexible interactions, for they can be easily moved and organized to reflect the user's state of knowledge and as a way to input new search directions. Entity-based systems have been shown to substantially reduce the need for typing, which make them especially useful for touch devices (Klouche et al., 2015). They have also been shown to foster more active behavior from users in exploratory settings, with more queries submitted and more relevant information found per unit of time as well as more branching and revisits in the search trail (Andolina et al., 2015).

3. System design

In this section, we identify design goals and describe how they were implemented in the QueryTogether system. The main theme we identified is the need to effectively support exploratory search in a collaborative and spontaneous search setting. The challenge is how to adapt exploratory features developed for single-user scenarios in a collaborative search tool by making sure to provide a good support for exploration at both the system and the interface level. Another theme that has emerged from studies is that collaborative search happens in a variety of situations and with different devices. The challenge is designing for a wide range of devices with different form factors and different input modalities. Finally, it has been noted that co-located collaborative search, although often preferred to remote collaboration, may perform less effectively (González-Ibáñez, Haseki, & Shah, 2013). In their study, González-Ibáñez et al. (2013) demonstrated that, for an exploratory search task, remotely located participants were able to explore better than co-located teams, meaning that more independence led to more diversity in information resources, which helped explore a greater variety of relevant information. Having more social presence increased interactions among the participants, but these interactions were often found to be distracting for a time-bound task. The design challenge here is how to incorporate the best of the co-located and remote approaches by making sure that people can take advantage of the more tightly coupled collaboration typical of co-located situations but also of the more independent, loosely coupled form of collaboration happening when interacting remotely.

Based on the current trends and envisioned collaborative-search practices, we hypothesized that an effective interface for co-located, collaborative exploratory search should support entity-centric exploration but also enable the flexible use of devices and support diverse working styles.

3.1. Design goals

- *Entity-centric exploration*. The units of search and collaboration can be any information entities – such as documents, keywords, and authors – that can be shared for collaboration or used as queries to trigger exploration. The design should also provide different starting points for exploration, including not only entities suggested by peers but also entities suggested by the system. System suggestions should be provided every time a new query is triggered, so users are always provided with possible directions for future exploration. In both cases the suggested entities should be encapsulated in *interactive search objects* that can be directly used to trigger new queries and explore new directions.
- *Flexible use of devices*. To study the effect of entity-centric exploration in a scenario that reflects the current trends as closely as possible, one design goal is to make the system usable from a variety of devices and thus support different modalities (e.g., mouse and touch) and different platforms. To facilitate interaction on smaller devices (and on touch screens in general), the main features such as querying and sharing should not necessarily require typing. Enabling typing-free interactions may also prevent unnecessary overhead when accepting system suggestions and thus lead to less distraction and better exploration.
- *Support for diverse working styles*. Previous work on co-located collaboration has stressed the importance of supporting a variety of working styles ranging from individual work to tight collaboration (Scott, Carpendale, & Inkpen, 2004; Tang, Tory, Po, Neumann, & Carpendale, 2006). It is important to allow for various degrees of coupling as at times, the work is more efficient if it is performed by an individual or loosely coupled. This is also important due to the fact that in some instances, it might be appropriate to allow for maintaining privacy of the information being manipulated by participants (Stefik et al., 1987). Moreover, the system should allow for flexible switching between different working styles. Users should have the option to work independently and to decide if and when to share and whether to share privately or publicly. While this could lead to more effective collaboration (González-Ibáñez et al., 2013), it could also be beneficial from a privacy perspective, as users decide what to share without needing to disclose their entire search log.

The practical implementation of the QueryTogether system consists of two parts, the user interface and the search engine, which are described in detail in the following subsections.

3.2. User interface design

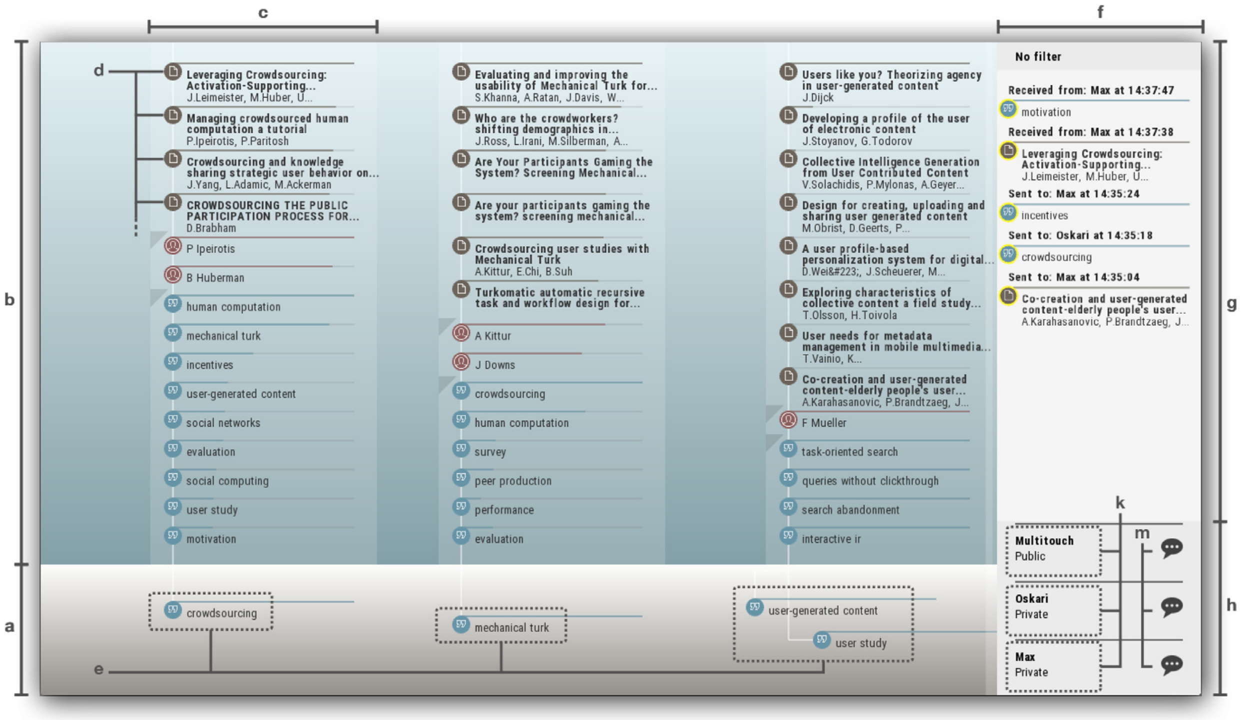
The workspace is divided into two parts: the query area (Fig. 2a) at the bottom and the results area (Fig. 2b) on top. The side panel (Fig. 2f) is collapsible and always available on the right edge of the screen. It contains the reading list/share history (Fig. 2g) – where the user can visualize all saved and shared information in descending chronological order – and the user list (Fig. 2h) – where each user's name is displayed as a label along with his or her share status ("public" for shared devices and common work spaces or "private" for users with individual/private devices) (Fig. 2k).

The system uses and presents all information in the form of entities, i.e. interactive objects that embody snippets of different types of information. In the current instantiation, entities are of three types: documents, authors, and keywords. Each entity is represented by an icon, a label, and a relevance gauge and can be dragged across the workspace. This approach allows the user to make intuitive associations and to use any encountered information as a new starting point for exploration. Additional interactions include: accessing an entity's content by tapping its label and saving it by tapping its icon. Saved entities are highlighted and can be found in the reading list in the side panel.

All search queries consist of an entity or a group of entities of any type (Fig. 2e). Queries are formulated by dragging existing entities to the query area at the bottom. When entities are brought close enough together, they are considered to belong to the same group, which is made visible through a visual link. When a specific topic of interest cannot be found among existing entities, double clicking on the query area will show a textbox that allows the user to create an entity based on a custom expression.

Sharing is performed by dragging an entity to the chosen user. The recipient will instantly receive a new instance of the sent entity in his or her side panel. If the side panel is closed, a visual notification in the corner informs the user of the number of new entities received. Next to each user label, a "Message" icon (Fig. 2m) allows the user to send a short message along with an entity.

To facilitate exploration based on saved and shared entities and documents, the reading list/share history can be filtered according to a chosen collaborator, simply by tapping his or her name. Filtering based on a collaborator that uses a personal device will show only entities and documents sent to and received from that user. Filtering based on the moderator, or any collaborator using a public workspace (e.g., through a shared monitor, large screen or projector) will display the content of the common collection shared among all users. Filtering based on one's own name will display only entities that have been saved locally and ignore anything sent or received remotely.



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No filter
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incentives
Sent to: Oskari at 14:35:18
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Co-creation and user-generated content-elderly people's user...
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Max
Private

Fig. 2. The interface is composed of (a) the query area and (b) the results area. Main interface elements include: (c) search streams; (d) three types of entities: documents (brown icons), authors (red icons), and keywords (blue icons); (e) simple or composed queries; (f) the side panel, which is composed of (g) the reading list/share history and (h) the user list, with (k) a list of users and (m) a messaging option. The user composes new queries by dragging entities to the query area. A custom expressions-text input field is created by double clicking/tapping on an empty space in the query area. Entities can be saved to the reading list by dragging and dropping. The reading list also displays entities sent by collaborators. The user list shows online collaborators. Entities can be shared by dragging them to the recipient in the user list. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

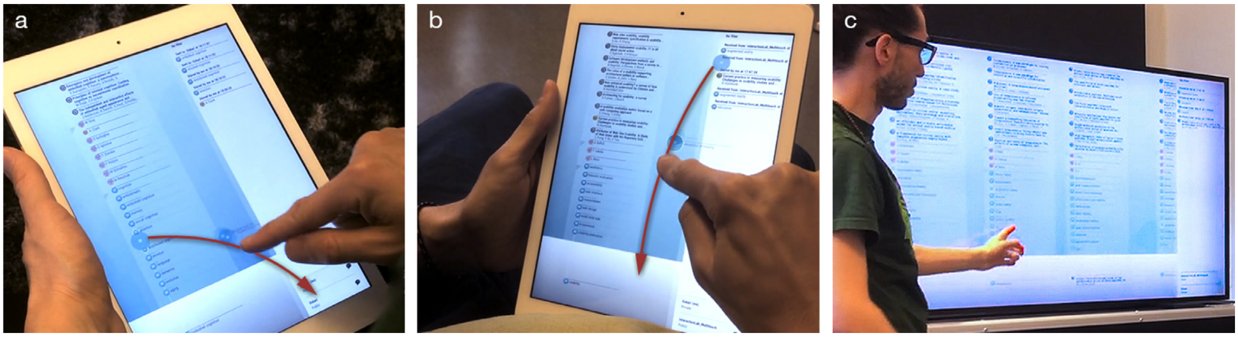


Fig. 3. This sequence illustrates the coordination and exploration process between collaborators: a) from the results of a search, User 1 chooses an entity - in this case a keyword - to send to User 2. User 1 drags the chosen entity to User 2's label in the user list. b) The received entity appears in User 2's reading list, along with information on the sender and the time it was sent. User 2 can then use it as an exploration trigger to start a new search stream by dragging the received entity to the query area. c) In the same way, entities can be sent to User 3. In this case, User 3 uses the system on a common workspace on a large screen and is set as public, so entities on the large screen are shared with all collaborators.

3.3. A walkthrough example

Max, Anna, and Oscar are three computer science students. They have teamed up to present a common project in the context of a workshop on the semantic web. They meet to look for ideas as they only have a superficial knowledge of the topic. Max and Oscar take out their tablets, while Anna takes control of the shared large multi-touch screen, assuming the role of the public user and moderator of the session.

As they each log on to the collaborative search system, their names stack up in the user list on each device. They agree to start by exploring the topic of “semantic web” at large, to find inspiration and become more familiar with related subtopics. Anna starts by tapping somewhere in the query area of the shared screen, which opens a local text box. A soft keyboard pops up, with which she types “semantic web.” Based on that query, the system returns a variety of related documents and keywords organized in a vertical stream. They discuss and review the keywords suggested by the search engine that seem to be the most central. They eventually agree that Oscar will further investigate the topic “ontologies” while Max will explore “web mining.” On the shared screen, Anna drags the keyword “ontologies” from the result stream to the user label “Oscar” in the user list (Fig. 3a). A new instance of the keyword appears instantly in Oscar’s side panel with the mention “Shared by Anna (Moderator) at 10:36:17”. Anna then does the same with the keyword “web mining” to Max. Without having to type anything, Oscar privately drags the freshly received keyword on his device toward the query area, which returns a new stream of articles and keywords all related to “ontologies” (Fig. 3b). He reads the abstracts of the retrieved articles and performs a few follow-up searches based on the related keywords. The new result sets appear as parallel streams on his interface, allowing him to compare their contents. In the same way, Max explores information related to “web mining.”

As they both encounter interesting documents and keywords, they send them to the large screen by dragging them over to Anna’s user label. After a little while, they decide to stop collecting new material to discuss the shared content. Anna leads the discussion on the large screen (Fig. 3c). As they review the outcome of their individual searches, they agree on which documents to keep in the list and which to dismiss. To remove an entity or a document from the list, they simply drag it out of the side panel. In the end, all three participants share the same collection of a few highly relevant documents that will make for an excellent basis to start their project.

3.4. The search engine

In order to support the document retrieval and entity oriented coordination, the search engine was designed to support two main functions: entity ranking and document ranking.

Entity ranking computes a ranking for entities given the composed query. The key idea behind the entity ranking is that the entities offered to the user by the system are based on centrality estimation given the query. For example, if the user searches for “information retrieval,” she is expecting back not only entities that occur in the top ranked documents, but also ones that are central for the field of information retrieval.

Document ranking computes a ranking for the resulting documents given the composed query. Conversely to the entity ranking, document ranking is based not on centrality but solely on relevance estimation given the query.

We used a document set including more than 50 million scientific documents from the following data sources: the Web of Science, prepared by Thomson Reuters, Inc.; the Digital Library of the Association of Computing Machinery (ACM); the Digital Library of the Institute of Electrical and Electronics Engineers (IEEE); and the Digital Library of Springer. Information on each document consisted of the following: the title, abstract, author names, and publication venue.

3.4.1. Entity ranking

We represent the underlying database as an undirected entity-document graph, where each document, keyword, and author are represented as vertices, and the edges represent their occurrence in the document data.

The centrality ranking is based on the user's relevance feedback on vertices determined by dragging them into the query area. Each cluster in a query area represents a separate query that consists of a set of vertices. We use the personalized PageRank method (Jeh & Widom, 2003) to compute the ranking of the vertices. The set of vertices that the user has chosen to be part of an individual query form the personalization vector that is set to be the prior for the PageRank computation (Jeh & Widom, 2003). We compute the steady distribution by using the power iteration method with 50 iterations. The top $k = 10$ nodes from each entity category (keyword, author) are selected for presentation for the user.

3.4.2. *Document ranking*

The document ranking is based on a language modelling approach of information retrieval (Zhai & Lafferty, 2004), where a unigram language model is built for each document, and the maximum likelihood of the document generating the query is used to compute the ranking. We use Jelinek-Mercer smoothing to avoid zero probabilities in the estimation.

Intuitively, separating the entity ranking and document ranking approaches makes it possible to compute a limited set of entities that are likely to be the most important in the graph given the user interactions and allows users to target their feedback on a subset of the most central nodes given the interaction history of the user in any subsequent iteration. At the same time, the document ranking enables accurate and well-established methodology for ensuring relevance of the documents.

4. User study

4.1. *Research questions*

To demonstrate that entity-based interfaces on heterogeneous devices improve support for collaborative searches, we conducted a user study. To investigate the improvement given by QueryTogether relative to the baseline, we considered effectiveness, collaboration support, and engagement (see Sections 4.7.1, 4.7.2, 4.7.3):

1. Effectiveness: Does the QueryTogether system improve the search session effectiveness of retrieved information when compared to the baseline system?
2. Collaboration: Does the QueryTogether system enhance collaboration or lead to more balanced contribution within the group of participants when compared to the baseline system?
3. Engagement: Does the QueryTogether system lead to more engaging search behavior when compared to the baseline system?

Additionally, we aimed to investigate how and in terms of what aspects the collaboration changes, focusing on the use of searchable objects/entities, collaboration styles, and heterogeneous devices:

1. Entities as searchable objects: What is the extent of use of entities as searchable objects in conversation or through the use of QueryTogether?
2. Collaboration styles: Does the collaboration differ in tightly or loosely coupled work styles (Scott et al., 2004; Tang et al., 2006) or transitions between these?
3. Heterogeneous devices: Are there differences in how participants attend to the different devices?

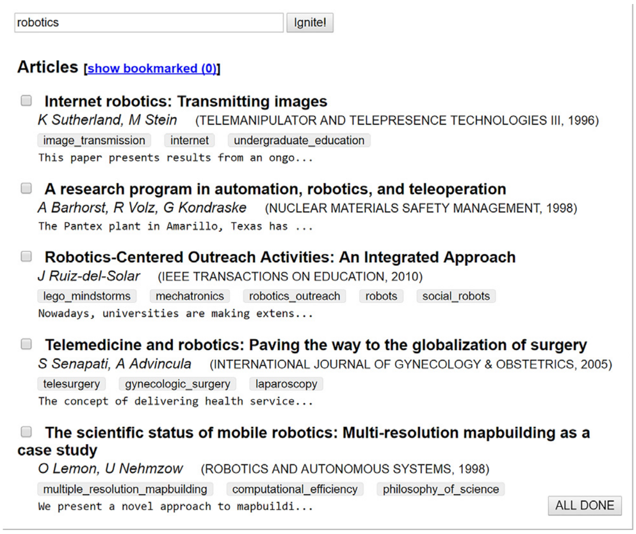
4.2. *Experimental design*

The study followed a within-groups design with nine groups and two system conditions. Nine in-person teams of three people were assigned a collaborative search task. The system conditions were the full QueryTogether and a baseline version of the system that did not have the design features of QueryTogether. Each group performed two tasks: one with the support of QueryTogether and one with the baseline. The conditions and tasks were counterbalanced by changing the order in which the two tasks were performed and the order in which the groups were subjected to each condition.

4.3. *Baseline*

As the number of factors affecting the design did not allow for baselines where each factor would be studied in isolation, we designed a baseline system based on the following rationale:

- *De-facto practice.* As the study did not focus on a single isolated system factor but rather a whole system design, we wanted to compare QueryTogether with a set of tools representing an authentic *de facto* work practice. A recent survey study (Morris, 2013) suggested that despite the increasing availability of tools designed specifically to support collaborative search scenarios, users may be reluctant to adopt them. The de-facto practice of performing collaborative information seeking and search is based on repurposing everyday communication technologies, such as online document sharing combined with conventional information search systems.
- *All other system features being equal.* As the study compared a system with the proposed design features, and a setup where the participants were using de-facto practice, we wanted to ensure that all other system features were as equal as possible. These



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ALL DONE

Fig. 4. A screenshot of the baseline system. It uses the same underlying dataset and ranking model as the QueryTogether system. The interaction with the system is limited to typed queries and the result presentation relies on a ranked list. Papers can be bookmarked to build a personal list. Such a list is hidden by default but can be expanded by clicking on the link “show bookmarked”.

include the database and the indexing and ranking functions of the search engine. In other words, we used the exact same underlying database, the search engines used the same state-of-the-art ranking function, and we indexed the data using the same inverted indexing technique. This ensured that none of these would become confounding factors in the study.

- *Interface mimicing.* We wanted to mimic the interface design of publicly available Web search engines and digital library search systems with which the participants would be familiar. These interfaces typically display a search box and a list of query results.

The baseline, illustrated in Fig. 4, was implemented based on this rationale. The baseline was a control condition that mimicked the conventional search interfaces, allowed for isolating confounding factors related to data or search engine functionality, and enabled the users’ de-facto collaboration practice to be conveyed by combining the baseline system with the tools that the participants would use in real-life situations.

We selected Google Docs as the information gathering and sharing platform, as this is the most commonly used collaborative platform available and the participants were likely to be familiar with the platform.

4.4. Procedure

The experiments took place in a dedicated interaction laboratory, shown in Fig. 5. The participants in the group were first debriefed on the experimental procedure and the purpose of the study. Then, they signed an informed consent form to take part in the experiment. The participants were also told that they were free to withdraw from the experiment at any moment with no consequence. The experimenter then illustrated the system, the interface functionalities, the devices, and the tools that the participants

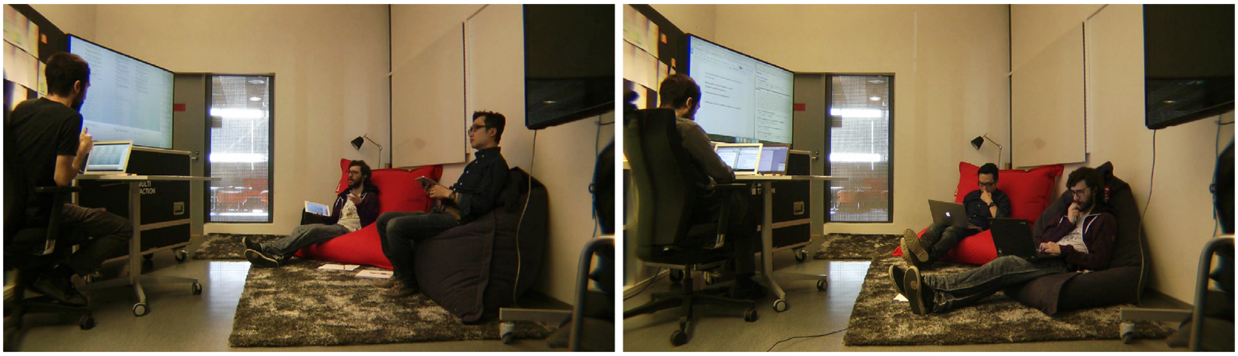

Fig. 5. The experimental setting with the two experimental conditions. In the QueryTogether condition (left), two of the participants were equipped with tablet computers, and the moderator was equipped with a laptop computer. The QueryTogether was used in all of the computers. In the baseline condition (right), all the participants used laptop computers. The moderator screen was projected to the large screen in both conditions. The figures are captured frames from a video recording of an actual experimental session.

could use. Then, the participants were asked to try out an exemplary task. This ensured that the participants were aware of how to operate the system and use the tools and devices as intended. Prior to starting the actual session, each group first had to elect a moderator who would have the responsibility of leading the collaboration and managing the final outcome. After this, the experimented made sure that the participants agreed that the system functioning, the tasks, and the roles of the participants were clear, and the actual experimental session began.

Two of the participants sat in chairs with an optional table, and the moderator sat at a separate desk. The three participants were placed in a triangle facing each other at a distance of approximately 2 m to make it easy to see each other and communicate. When using the baseline, all participants used laptop computers. When using the QueryTogether system, two participants used tablets (9” diagonal screen size), and the moderator used a laptop computer. In both conditions, the moderator’s computer was mirrored onto a large screen that faced the other two participants.

The participants had 20 min to complete the task with each system. After completing the task, participants were asked to fill out the User Engagement Scale questionnaire. The entire experimental session lasted about 80 min. Each participant received two movie tickets as compensation for participating.

4.5. Participants

Altogether, 27 people (8 women) were recruited to take part in the experiments. Participants were recruited from the computer science department of two Universities, and they all had at least some research experience. The participants were assigned to one of nine groups of three people each. Participants in the same group knew each other. Recruiting was done via word-of-mouth and specialized mailing lists. To reduce the effect of social dynamics during group formation, which could distract from the main task (Tuckman, 1965), and to study a more realistic situation, the recruiting message specified that participants were supposed to know each other, thus requiring to sign up in groups of three.

The mean age was $M = 29.30$ ($SD = 3.71$) and the levels of education were: 26% PhD, 52% master’s degree, 11% bachelor’s degree, 11% high school. When asked to self-assess their ability to successfully find information using a Web search engine, 63% chose “average” and 37% chose “expert.”

4.6. Tasks

The task was created to support an exploratory search scenario. To ensure that the participants had at least some research experience while not being experts on the proposed topics, we used a screening questionnaire. The task was formulated as follows: *Your group has been asked to write a scientific review on topic X. As part of the task, you have to perform a bibliographic search on topic X. You have 20 min to find at least 20 relevant papers that cover as many subtopics as possible.* Two topics were used in the evaluation sessions: “crowdsourcing” and the “semantic web.”

Participants in the QueryTogether condition collected the relevant papers in the reading list (Fig 2g), while participants in the baseline condition used a shared Google doc. All the sessions lasted 20 min. Although participants could collect as many relevant papers as needed, they were instructed to keep only the 20 most relevant papers found and discard those that exceeded that quota.

4.7. Data collection and analysis

The data collected during the study were based on observations, questionnaires, logged data, and interviews. The entire trial was video-recorded to allow offline analysis. Two researchers reviewed the recordings of the session independently, transcribing the utterances that took place. The transcriptions were subsequently coded in terms of types of utterances and collaboration strategies. The same researchers then went through a second cycle of video analysis to quantify the usage of the large public screen. Transcription and coding were performed using the software ATLAS.ti. Among other things, the software enabled associating timestamps to different transcriptions and codes.

In order to operationalize the research questions, a set of actionable measures were defined to quantify each of the aspects: effectiveness, collaboration, and engagement. In particular, we analyzed collaboration based on contribution balance, usage of the public screen, and the quantity and type of discourse produced while solving the task. Qualitative analysis of the video recordings were also performed in order to better understand the patterns of collaboration that took place.

4.7.1. Effectiveness

In order to measure the quality of the information retrieved, we quantified the effectiveness of the search session. Since the baseline returns lists of documents while QueryTogether returns lists of mixed-type entities, we chose to solely measure the quality of the retrieved documents. Our main effectiveness measure is an adapted version of *S-Recall* (Zhai, Cohen, & Lafferty, 2003) for the search task outcome, as the task was to find at least 20 relevant documents that would cover as many subtopics as possible. The subtopic retrieval measure reflects the goal of exploration, for it measures the coverage of many different subtopics rather than merely relevance. This means that the usefulness of a document depends on other documents and their topical distribution (as determined during the search session.)

The original formulation of S-recall reflects the proportion of unique subtopics covered by a ranked list. Such a definition is meant for single queries and does not fit well the case of search sessions based on multiple iterations of queries. We thus adapted the S-Recall measure to reflect the proportion of relevant and unique subtopics covered by a set of documents. As an approximation of the subtopics covered by a given document, we used the author-defined keywords of that document that were available as metadata in our dataset. S-Recall was computed over time in order to get a sense of how fast users were able to reach a good coverage of relevant information across different subtopics.

Additionally, we used more traditional information retrieval metrics such as precision, recall, and F-measure. All the measures were calculated at the group level to quantify the overall quality of the information retrieved by the group during the search session. The measures were computed using a pool of documents constructed from the system logs. This ensured that the pool contained all documents found by any of the groups. Domain experts assessed the relevance of each retrieved document on a binary scale: relevant or irrelevant. Author-defined keywords for each relevant document were considered relevant subtopics.

4.7.2. *Engagement*

The degree of user engagement is a strong indicator of search performance (White & Roth, 2009). For example, the extent to which the user is focused on the task can indicate whether the system is fulfilling its role in supporting search activities (White & Roth, 2009). To evaluate the engagement, we used the User Engagement Scale (UES) for exploratory search (O'Brien & Toms, 2013). The UES questionnaire in its original form includes 31 questions in six different dimensions: Aesthetics (AE), Focused Attention (FA), Felt Involvement (FI), Perceived Usability (PUs), Novelty (NO), and Endurability (EN) aspects of the experience. Here, we use the revised form of UES comprising 28 questions and four factors. With respect to the original version, while FA, AE, and PUs remained distinct factors, items from the NO, FI, and EN subscales were joined to form one factor (O'Brien & Toms, 2013). In accordance with (O'Brien & Toms, 2013), for each question in UES, participants indicated the extent to which they agreed with each statement about their exploratory search experience on a 7-point Likert scale from strongly disagree (1) to strongly agree (7).

4.7.3. *Contribution balance*

The balance of contribution between group members gives an indication of the quality of the collaboration in both conditions, as groups for which all the relevant subtopics were found by only one or two members may be considered to be collaborating less than those groups in which each member found a similar number of relevant subtopics. Previous studies (Salomon & Globerson, 1989) revealed that unbalanced contributions lead to a loss of motivation in team members, which further leads to the loss of productivity. The reasons for this include the several negative social dynamics happening in teams with unbalanced contributions. In such teams, for example, the less hard-working members may suffer from the *free-rider* effect, deciding that their efforts are dispensable, whereas the hardest-working members, who do most of the work for the whole team, may gradually decide to expend less mental effort to avoid the feeling of being taken advantage of, the so-called *sucker* effect (Salomon & Globerson, 1989).

We considered the number of unique and relevant subtopics each group member contributed and used the Gini coefficient of inequality to measure the balance of contribution. This measure is often used to measure inequality of income distribution (Firebaugh, 1999), but it has also been used to measure participation across group members using an interface (Rogers, kyung Lim, PhD, & Marshall, 2009). It is a ratio measure that can be used to compare inequality across cases with different overall measures. The Gini coefficient ranges from 0 (*no inequality*) to 1 (*total inequality*). In our case, smaller values of the coefficient would indicate a more equitable distribution of unique and relevant subtopics.

4.7.4. *Public screen usage*

The attention to the common public screen was also considered an the indicator of the quality of collaboration. In particular, this measure reveals how participants took advantage of heterogeneous devices available. Video recordings were analyzed by two independent researchers who counted the number of glances toward the public screen by those participants using private devices. The participant acting as moderator was excluded from this calculation as (s)he was working directly on the public screen. One session from the baseline and one from QueryTogether were randomly selected to be coded by both raters to assess the interrater reliability. Cohen's kappa score was substantial (0.72).

4.7.5. *Usage of entities in conversation and QueryTogether*

The usage of entities in QueryTogether was derived from system logs. To understand the usage of entities in the conversation, the type of discourse produced while carrying out the task was analyzed. For this purpose, we developed a coding scheme that included six kinds of communicative acts used during the task: sharing (S), sharing prior knowledge (PKS), clarification questions (CQ), queries (Q), answers (A), and reports (R). In particular, sharing was further qualified based on the specific entity it regarded (documents: D, authors: A, or keywords: K). We defined sharing as utterances that contained an entity that could be used as searchable object by other collaborators. For example, "I think Mechanical Turk is a good keyword" would be coded with S(K), meaning a sharing of a "keyword" entity. For the S code, we mainly considered the cases in which the entity was mentioned for the first time in the session. The cases in which the entity was not yet acknowledged by other collaborators but was mentioned for a second time by the same person were also coded with S. The cases in which it was clear that the sharing derived from prior knowledge were coded with PKS, for example, "I know Tim Berners-Lee is the father of Internet." We defined clarification questions as those utterances asking for more information about an entity, for example, "What's Mechanical Turk?" Queries were defined as generic questions about an entity, such as, "Did anyone use collaborative computing (a previously shared keyword)?" Answers were defined as replies to clarification questions or queries. Reports were defined as coordinated utterances reporting actions done with entities, such as, "Don't do collaborative computing. I did that already" or "I'm already looking at social computing." One session from the baseline and one from the QueryTogether condition were randomly selected to be coded by both raters to assess the inter-rater reliability. Cohen's kappa score was substantial (0.77).

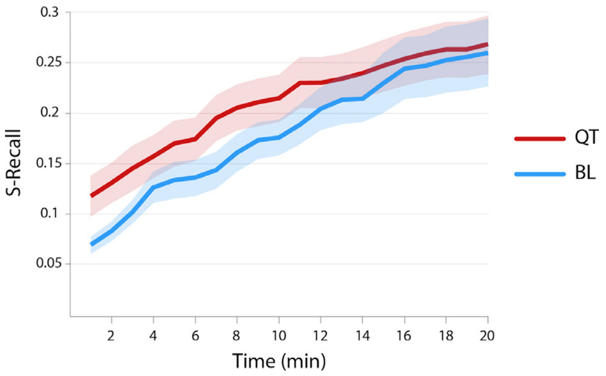

Fig. 6. S-Recall over time (averaged across groups).

4.7.6. *Collaboration styles*

The degree to which collaborators work closely together or independently is referred to as tight versus loose coupling (Dewan & Choudhard, 1991). To understand the styles of collaboration in QueryTogether and the baseline, we measured the intervals of time spent in *tightly coupled collaboration* and in *loosely coupled collaboration*. An interval of time was coded as tightly coupled collaboration (TC) when group members engaged in intense verbal communication. Conversely, the intervals of time characterized by absence of communication or one-way communication from one group member to the others were assigned the code referring to loosely coupled collaboration (LC). One session from the baseline and one from the QueryTogether condition were randomly selected to be coded by both raters to assess the inter-rater reliability. Cohen's kappa score was substantial (0.66). The coded transcriptions were also used to measure the *support to flexible coupling* by counting the number of transitions between the two modalities.

5. Findings

The findings from our evaluation can be grouped by three themes: effectiveness, user engagement, and collaboration. Qualitative analyses were also carried out to examine in more detail the patterns of collaboration and interaction that took place.

5.1. *Effectiveness*

The average number of queries per session was 32.89 ($SD = 11.62$) for QueryTogether, and 28.89 ($SD = 12.70$) for the baseline. Fig. 6 shows the S-recall for both system conditions averaged over groups for both system conditions. The users find approximately equal subtopic coverage for the search session using both systems. However, the results show how users in the QueryTogether condition were able to cover a large part of relevant subtopics in the earlier phase of the search session than users in the baseline condition.

The precision, recall, and f-measure values at group level for QueryTogether were $M = 0.45$ ($SD = 0.20$), $M = 0.19$ ($SD = 0.07$), and $M = 0.24$ ($SD = 0.07$), respectively, and the same values for the baseline were $M = 0.49$ ($SD = 0.32$), $M = 0.21$ ($SD = 0.06$), and $M = 0.25$ ($SD = 0.06$), respectively. Paired *t*-tests showed no significant differences among the two systems in effectiveness.

5.2. *User engagement*

Table 2 shows the results from the UES questionnaires. A Wilcoxon signed rank test with Holm-Bonferroni correction indicated that QueryTogether UES scores were statistically significantly higher than the baseline. The results suggest that user engagement was improved in the QueryTogether condition.

5.3. *Contribution balance*

The per-group Gini coefficients of the number of unique and relevant subtopics each group member contributed were $M = 0.33$ ($SD = 0.17$) for QueryTogether and $M = 0.70$ ($SD = 0.14$) for the baseline. A paired *t*-test shows that the difference is significant ($t(8) = 5.36$, $p < .01$), which indicates that a more balanced participation was observed for QueryTogether than for the baseline (Fig. 7).

Table 2

Results from UES Questionnaire. A Wilcoxon signed rank test with Holm-Bonferroni correction indicated that QueryTogether UES scores were statistically significantly higher than the baseline.

	QueryTogether			Baseline			Comparison
	M	SD	Mdn	M	SD	Mdn	Wilcox. Test
PERCEIVED USABILITY							
I felt discouraged while using this system	2.70	1.44	2	4.22	1.80	5	
I felt frustrated while using this system	2.89	1.53	2	4.30	1.88	5	
I felt annoyed with using this system	2.81	1.61	3	4.07	1.90	5	
This search experience did not work out the way I had planned	3.56	1.67	4	4.59	1.60	5	$Z = 2.10$
I could not do some of the things I needed to do using this system	4.22	1.80	5	4.74	1.65	5	**$p = .04$**
I found this system confusing to use	2.85	1.43	2	3.04	1.74	3	
Using this system was mentally taxing	2.70	1.38	2	3.41	2.02	3	
This search experience was demanding	3.81	1.30	4	3.93	1.69	4	
I felt in control of the searching experience	4.44	1.22	5	3.93	1.38	4	
NOVELTY, FELT INVOLVEMENT, ENDURABILITY							
I felt interested in my searching tasks	4.89	1.28	5	3.41	1.50	3	
The content of this system incited my curiosity	5.22	1.12	5	3.15	1.43	3	
My search experience was fun	5.33	1.14	5	2.59	1.22	3	
I felt involved in the searching tasks	5.19	1.47	5	3.48	1.72	3	$Z = 4.00$
My search experience was rewarding	4.44	1.22	4	3.19	1.30	3	**$p = .0002$**
I would recommend this system to my friends and family	4.30	1.32	5	2.37	1.24	2	
I was really drawn into my searching tasks	4.22	1.15	4	2.89	1.31	3	
I consider my search experience a success	4.19	1.59	5	3.19	1.33	3	
Searching using this system was worthwhile	4.85	1.43	5	2.89	1.22	3	
AESTHETIC APPEAL							
The screen layout of this system appealed to my visual senses	5.63	1.11	6	2.67	1.47	2	
The system interface is aesthetically appealing	5.67	1.24	6	2.52	1.31	3	$Z = 4.31$
The system interface is attractive	5.48	1.22	6	2.15	1.20	2	**$p = .0001$**
I liked the graphics and images used by this system	5.59	1.28	6	2.33	1.30	2	
FOCUSED ATTENTION							
I was so involved in my searching task that I lost track of time	3.59	1.55	3	2.78	1.48	3	
The time I spent searching just slipped away	3.89	1.58	4	2.78	1.60	3	$Z = 2.41$
I lost myself in this searching experience	3.26	1.53	3	2.37	1.28	2	**$p = .03$**
I blocked out things around me when I was using this system	3.52	1.55	4	2.48	1.53	2	
I was absorbed in my searching task	4.11	1.48	4	3.11	1.60	3	

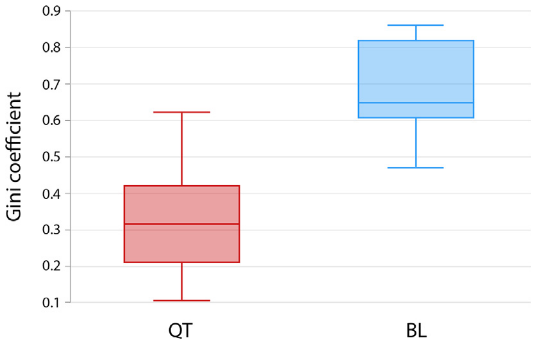

Fig. 7. Gini coefficient of the distribution of unique and relevant subtopics found by individual group members within a group.

5.4. Interaction analyses

5.4.1. Entity usage

The average number of shared entities was 30.44 ($SD = 8.05$), 3.22 of which ($SD = 2.44$) were search cues (keywords or authors). In the QueryTogether condition, an average of 32.33 search terms were used. In only 47% of the cases ($M = 15.22$, $SD = 8.30$) did users rely on the keyboard to generate new query terms. In the remaining 53% of the cases, query terms were generated by dragging a system or peer suggested entity to the dock. More specifically in 46% of the cases ($M = 15.00$, $SD = 6.84$), the used search terms were suggested by the system, while peer suggestions accounted for 7% of the cases ($M = 2.11$, $SD = 1.83$).

Fig. 8 shows how entities were used in the conversation that took place while carrying out the task. While the sharing of entities was almost the same for QueryTogether and baseline, in the QueryTogether condition, we observed slightly more usage of entities in

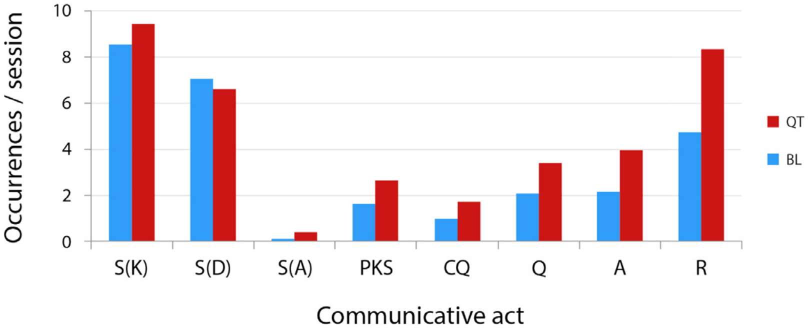

Fig. 8. The usage of entities in the conversation that took place while carrying out the task. In the X axis the different kind of communicative acts coded: S(x) = sharing, $x \in$ {K = keyword, D = document, A = author}, PKS = prior knowledge sharing, CQ = clarification questions, Q = queries, A = answers, R = reports. In the Y axis the average frequency of those codes in a session.

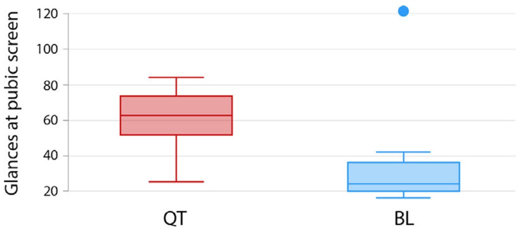

Fig. 9. Number of glances at the large public screen.

the context of sharing prior knowledge, clarification questions, general queries, answers, and reports. The low frequency of the event S(A) also shows the scarce role played by the entity "author" in the study.

5.4.2. Public screen usage

In QueryTogether participants looked at the large public screen 60 times on average ($SD = 18.32$), while in the baseline the number of glances at the public screen was $M = 36$ ($SD = 33.28$). An inspection of Fig. 9 shows that the number of glances at the public screen was generally higher in the QueryTogether condition.

5.4.3. Collaboration styles

The time spent in tightly coupled collaboration was $M = 13.29$, $SD = 5.13$ min in QueryTogether, and it was $M = 11.49$, $SD = 7.18$ min at the baseline. The number of transitions between tightly coupled and loosely coupled collaboration was $M = 10.11$ ($SD = 4.78$) for QueryTogether and $M = 6.33$ ($SD = 4.72$) for the baseline. This result suggests that QueryTogether supported a more flexible coupling. By inspecting Fig. 10 is it possible to get a qualitative overview of how different styles of collaboration took place in both conditions.

5.4.4. Rate of verbal communication

The mean number of utterances per minute was calculated by running a matlab script over the timestamped transcriptions. Fig. 11 shows the change over time in the rate of dialogue. The chart shows a similar amount of dialogue production in the first part of the session between the two conditions, while more dialogue is produced by participants in the QueryTogether condition during the second part of the session. This is compatible with what is suggested by Fig. 10, which showed that, compared to the baseline, the second part of the session for QueryTogether was characterized by more tightly coupled collaboration, thus having more intense verbal communication.

5.4.5. Collaboration and coordination strategies

Fig. 10 provides a general overview of how different styles of collaboration took place in both conditions. In this section we start from qualitative analyses of video recordings and logs of the sessions to further understand the patterns of collaboration and coordination strategies that emerged during the study. The way the groups initiated and managed their participation was found to vary across sessions regardless of the condition.

Groups initiated their collaboration, either by working on their own or establishing common ground based on initial searches and prior knowledge, or by dividing the work among team members. The differences across conditions regard the way in which those strategies were implemented. For example, while a similar amount of entities were mentioned as part of the collaborative task

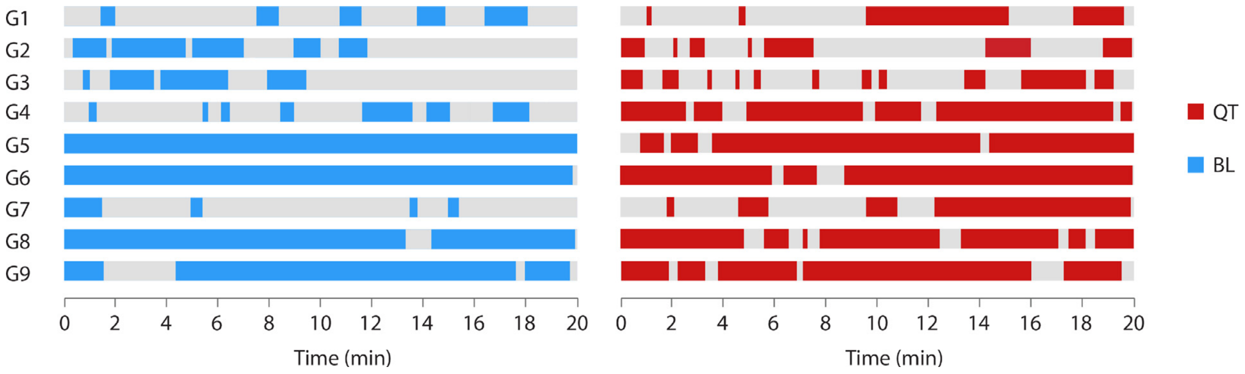

Fig. 10. The way in which groups collaborated in QueryTogether (QT) and the baseline (BL). Colored intervals (red for QT and blue for BL) indicate tightly coupled collaboration, in which group members engage in intense verbal communication. Light gray indicates loosely coupled collaboration where the verbal communication is either absent or one way from one group member to the other. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

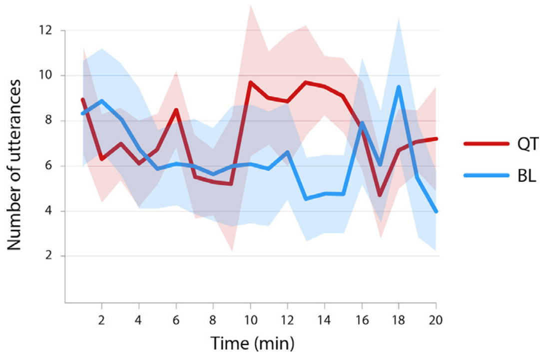

Fig. 11. Utterances per minute (averaged across groups).

(Fig. 8), in QueryTogether, the associated *searchable objects were readily available in the system* and could be used for search. Additionally, QueryTogether afforded strategies not easily implemented with the baseline. Below we use exemplary excerpts of conversations as the starting point for discussing those strategies.

In the QueryTogether condition, three groups initiated their collaboration with the *labor division*, compared to one case of the baseline. An example of labor division in QueryTogether was where participant P10 suggested to split the search effort and shared keywords with the other group members to facilitate the process:

Fragment 1	*Transcript 1*
P10 (Mod):	So: let’s share some of the keywords?
	(3.9)
P12:	I would try with just crowdsourcing in general =
P10 (Mod):	= Yes, but I meant, we can combine those keywords (.)
	I can take crowdsourcing with social networks, you take crowdsourcing with user studies
P12:	Ok
P10 (Mod):	So we can explore together
P11:	Alright

This fragment exemplifies the importance of the system suggestions in providing directions for exploration. The entity sharing mechanism also allowed every group member to easily take control over a specific search direction. On the other hand, in the baseline condition, situations such as these relied mostly on verbal communication, and this caused some difficulties. For example, when participant P5 suggested to P6 to investigate “reCaptcha”, P6 replied by asking to spell the keyword, which was an operation that took time and might have been distracting for other group members. In the baseline condition, the only participants able to more effectively share information were the moderators, as their search process was shown on the large public screen. The interaction, however, was still limited. As an example, participant P23 pointed at the large screen and asked the moderator to expand a particular abstract. In this situation, QueryTogether would have allowed the sharing of the actual entity, allowing P23 to take control over the document without needing to ask the moderator to perform actions on his behalf. Situations like these, seem to confirm the intuition gained from Fig. 9, in that the public screen could be used more effectively in QueryTogether. This also provides an example of unbalanced contribution in the traditional collaborative setting, with one person doing most of the work while the others provide guidance.

Another interesting example of collaboration that was supported by the searchable objects provided in QueryTogether regards the common ground establishment (Clark, Brennan, et al., 1991). An example is when P24 shared some prior knowledge and performed a *search cue suggestion*.

Fragment 2	*Transcript 2*
P24:	Do you know about this (2.5) I suppose you have heard about the Mechanical Turk kind of things?
P22 (Mod):	How does that work? *((P24 explains))* *((P23 pushes the Mechanical Turk keyword to the public display))*
P23:	I sent it
P22 (Mod):	So, alright (.) Mechanical Turk *((P22 drags the shared keyword to the query area and triggers a new query))*

In this fragment, P24 started a discussion about a relevant keyword in the domain in order to suggest using that keyword for the search. This resulted in a keyword sharing and a query triggered from the shared keyword. The keyword suggestion was used to facilitate discussion and establish a common ground among participants. It is also very interesting to note that the entity was actually sent to P22 by P23 and not by P24. Before P24 could finish his reasoning and share the entity, P23 had already suggested it from the system and could use it, in this case, for sharing it with P22. This shows the double role of entity recommendation in QueryTogether. One aspect is that it represents important triggers for discussion. The other aspect is that the system provides searchable objects for what could likely become a matter of discussion.

However, it is also worth noting that participants were sometimes so involved in their search task that they ignored the suggestion or delayed its acknowledgement. For example, when participant P01 suggested “Tim Berners-Lee” was the father of Semantic Web and shared the related entity, other group members initially ignored that suggestion; after about 7 min, P03 finally asked for clarification on the role of the suggested author, and discussion on the topic got started. This example supports the intuition that people in the QueryTogether condition were very involved in the search task during the first part of the session. They were often able to reach a good level of productivity soon without necessarily resorting to tightly coupled collaboration, and they spent more time in intense discussion only during the second part of the session, after having contributed consistently to the final outcome. Nevertheless, the example above shows how QueryTogether enabled the flexible change of collaboration style. When entities were not acknowledged soon in the baseline, they would be easily forgotten. In QueryTogether, however, participants could associate the verbal sharing of an entity with the sharing of the corresponding searchable object. The entity object would then stay visible in the share history (Fig. 2g). That enabled easy recall, allowing persons who were temporally working in an individual mode to finish their task, acknowledge the previously shared word, and switch to a tightly coupled collaboration form with other members of the group. The example above illustrates a peculiar pattern of collaboration of QueryTogether not being easily implemented in the baseline that we call *leave a note*. Video analyses show six occurrences of the pattern in QueryTogether, compared to one occurrence in the baseline in the entire study. This pattern could have partially contributed to the more flexible coupling observed in QueryTogether (cfr Section 5.4.3).

6. Discussion

The starting point of this research was that co-located collaborative search is increasingly observed in spontaneous situations (Brown et al., 2015; Morris et al., 2010a), while previous work mostly addressed bespoken arrangements such as tabletops, or distributed setups with desktop and mobile applications. Moreover, previous research highlighted the need to more explicitly support exploration in collaborative search situations (Hearst, 2014). The present work investigated whether an entity-based interface that successfully supports individuals in an exploratory search provides the right basis for designing for co-located collaborative search across personal devices and public screens. We developed goals for designing such a solution, particularly entity-centric design as well as support for a diversity of devices and working styles. The resulting system, QueryTogether, provides support for exploration at both the interface and the system level by combining a novel representation of entities as interactive searchable objects and smart entity recommendations. A study with 27 participants (nine groups) provided important insights on how our design improved collaborative search, while also revealing key challenges for future developments of the paradigm.

Contribution balance. Our study showed how our system design affected the way in which co-located groups collaborate in search. A main finding was the substantial difference between the Gini coefficients between the conditions, suggesting that QueryTogether led to more balanced participation in terms of contributions to the final outcome when compared with the baseline. A possible explanation is that engaging in an exploratory search task requires increased user effort as the topic, and, consequently, the key search terms are unknown at the beginning of the task. Evaluation apprehension, or similar negative social dynamics, may inhibit the more reticent participants to ask for help. In the baseline condition, many people limited their search to the obvious queries without being able to refine them. In contrast, in QueryTogether, the participants were able to avoid the typically observed situation in which one user searches while others watch and provide guidance. The explicit support for exploration, via system or peer suggestion of entities, always provided participants with possible directions for exploring an unfamiliar topic, thus making them more active. In particular, participants mostly used entities suggested from the system, whereas peer suggestions were used less. Prior research on remote collaboration has highlighted how participants often don't make heavy usage of specific coordination features involving peer recommendations (Morris & Horvitz, 2007). It is not surprising then that the same applies to co-located situations, where people have the possibility to coordinate by simply talking to each other. Our findings suggest that supporting system suggestions instead seems to be a more promising choice for the design of interfaces that foster equitable contributions in co-located collaborative search. Our study also suggests that the balance of contributions among team members may be associated with user engagement, which was found to be higher in the QueryTogether condition. This may have contributed to making participants less prone to social loafing, which is a phenomenon observed in individuals who rely on the group to exert less efforts (Williams & Karau, 1991).

Multi-device collaboration. Our results suggest that our design could be effective in a multi-device setting. In this paper, we envision a future in which people can start searching together at any time and with any available devices, including smartphones, tablet, and pervasive public-displays. While a significant portion of searches nowadays are executed on mobile phones, some complex tasks that require several iterations, such as those involving exploratory search of scientific literature, are still mainly performed on laptops. In the QueryTogether condition of our study, two of the three participants used tablet devices to perform exploratory search tasks. Although these kinds of tasks may seem easier on a desktop computer due to the intrinsic limitations of tablets smaller screen sizes (see Miller, Sumeeth, & Singh, 2011), as our measure of S-recall over time shows, our design allowed participants to be as effective with tablets as with laptops and more traditional search tools. Moreover, our analyses of effectiveness and verbal activity over time revealed that participants in the QueryTogether condition found most of the relevant subtopics sooner compared with participants who used the baseline, thus allowing more time for discussion and the establishment of common ground (Clark et al., 1991; Hertzum, 2008).

Entities as interactive search objects. Visualizing entities as interactive search objects seemed to have played an important role in supporting collaborative search on touch devices. We observed a reduced need for typing, with 53% of search terms created by dragging and dropping entities into the query area. Typing on soft keyboards is slower and more tedious than typing on physical ones (Hartmann, Morris, Benko, & Wilson, 2009; Hinrichs, Hancock, Carpendale, & Collins, 2007). This can negatively affect the efficacy and user experience of search applications, which are often heavily based on text entry activities. Our results are in line with findings from prior research (Klouche et al., 2015) indicating that, when given the opportunity, people prefer to directly manipulate search entities than type search terms on soft keyboards.

Flexible collaboration style. Our qualitative findings revealed some interesting details on how the collaboration took place. The analysis of the collaboration styles suggests that QueryTogether supported a more flexible coupling (Dewan & Choudhard, 1991), meaning that the system made it easy to switch between phases of individual work with little coordination, and phases of tightly coupled collaboration, in which participants engaged in intense verbal communication. Notably, the analyses revealed a peculiar strategy which seemed to be particularly suited for this kind of flexible collaboration, the possibility to leave a note for when others had time. The analyses further revealed how, in QueryTogether, most collaboration strategies typical of both conditions, such as, for example, the labor division and the establishment of common ground, could be more easily supported by the availability of the entities as searchable objects.

Common ground. Previous research demonstrated the importance of providing common ground in co-located interaction (Jacucci et al., 2009; Morrison et al., 2009). The higher lookup rate at the shared display suggests that better group awareness might have been achieved. Group awareness usually has a positive effect on the coordination of actions, anticipation, and assistance provided to collaborators with their local tasks (Gutwin & Greenberg, 2002). In particular, the higher awareness of publicly shared information suggests that the system facilitated the creation of a common understanding (Gutwin & Greenberg, 2002). This intuition is also supported by our results on the verbal usage of entities in QueryTogether, revealing how, in QueryTogether, more time was spent in creating common ground by sharing prior knowledge on entities, asking clarification questions, explaining, and reporting activities performed with entities. However, this sometimes led to long discussions that distracted from the main task. This suggests that the proper facilitation of common ground establishment is a challenge that requires further research.

Other implications of entity-based search. While this work suggests that entity-based search can effectively support collaborative information exploration, we believe that our findings may have implications for the design of search interfaces supporting a variety of search tasks beyond exploration. For example, even less explorative tasks include cases in which users search for a known item but do not recall either the title or any precise element from the content. In such cases, entity-based search may effectively support re-finding of such items by remembering an adjacent entity (e.g., an author, a similar document, or an imperfectly formulated topic), as making a query with the adjacent entity could trigger the system to recommend the desired item.

6.1. Open challenges

The work done in designing and studying QueryTogether uncovered some challenges that should be addressed in future research, which we describe below.

- *Supporting more direct access to entities.* Our design took a first step towards providing users with searchable objects related to their conversations. However, many entities related to the conversations were still missing from the proposed recommendations. The challenge for future research is understanding how entities can be extracted directly from the speech content and converted to searchable objects. This would require, among other things, the design of smart ways to extract real-time context-aware information about the conversation (McGregor & Tang, 2017), so that acceptable speech recognition accuracy could be achieved.
- *Identifying useful entity types.* The current implementation of QueryTogether has arbitrarily fixed entity types (i.e. documents, authors, and keywords). However, the most appropriate set of entity types depends on the specific scenario supported. In this case,

the Author type was not considered to be of much use to the participants (see Fig. 8), while some expressed interest in other possible types like the publication venue, for example. The challenge is understanding which entities to support in different situations.

- *Supporting more naturalistic tasks.* Our results reveal key insights and opportunities for how entity-centric exploration can be leveraged to support collaborative search with heterogeneous devices. While the proposed design proved to be effective on the task of collaborative literature search, understanding how to support more naturalistic tasks and informal conversations is a challenge that would require additional research.
- *Providing result previews on small devices.*Designing an interface for small devices involves making choices on what information to display, as the limited real estate of the devices' screen doesn't allow to show the same amount of information that is typically shown on interfaces designed for desktop environments. In QueryTogether, the preview of search results of scientific literature only included titles and authors of documents, leaving out information such as for example publication venue. While the same information was available in QueryTogether and the baseline, the difference in preview made a difference in how easily people could visually filter search results based on specific parameters. The challenge is to devise novel visualization strategies that would be able to fit the most important information with the least space possible, while maintaining legibility and skimmability.

6.2. Limitations

Evaluating collaborative search systems is a challenging task (Soulier, Tamine, Sakai, Azzopardi, & Pickens, 2016). Our study was a controlled within-groups user study in which the groups employed two system variants. This experimental design allowed for a direct comparison of the contribution of the various system variants and controlled for individual differences and behavioral patterns, which have been found to play a role in the perceived usefulness of search and recommender systems (Ekstrand, Harper, Willemsen, & Konstan, 2014; Hu & Pu, 2010). The advantages of a controlled study, however, come with limitations. The groups performed simulated work tasks with given topics, which may have affected the naturalness of user behavior. On the other hand, this mitigated the confounding factors potentially arising from the pre-knowledge of the groups about some given tasks.

The study used a single dataset from a single domain, which may limit the generalizability of our findings for scenarios involving data from other domains. On the other hand, the dataset was real, consisting of complete data from scientific articles consisting of over 50 million articles from several sources. This ensured that the coverage of the data was appropriate to support diverse search behavior and to allow for studying task performance with simulated work tasks.

We found that the QueryTogether system generally improves collaborative search in terms of several measures. However, we acknowledge that the contribution of the various features of the design were not investigated as independent factors in the present study. Consequently, our results suggest that multi-device co-located collaborative search can benefit from some or all of the features of the QueryTogether system. Future research should be aimed at confirming the effects of (1) input (entities vs. typed queries); (2) the collaboration mode (shared entity space vs. shared document space); and (3) devices (conventional typing devices vs. touch devices).

Finally, the questionnaires and qualitative analysis revealed participants' behavior, communication strategies, and collaboration styles that were not captured via the quantitative data-analysis. These analyses were based on qualitative and subjective feedback, and more research is required to confirm these results. However, despite these limitations, we believe that our quantitative and qualitative evidence on effectiveness, user engagement, contribution balance, and collaboration and communication styles show promise and open an interesting frontier for research targeting the improvement of the increasingly important field of collaborative information access.

7. Conclusions

Search is a social activity that pervades our daily life. The far reaching vision of this research is an environment able to understand our conversation, identifying key objects being referred to, and turning them into searchable entities. In this vision, search becomes a task carried out mostly by a system in the background, while users can focus their energy on discovery, sense making and collaboration. The assumption is that search is not the ultimate goal, but a mean for users who are engaged in solving complex tasks that transcend finding the information (Jacucci, 2016). With this work we took a promising first step in this direction. We introduced QueryTogether, a tool that facilitates collaborative search in spontaneous settings, by leveraging an entity-centric design based on entities as searchable objects and smart entity recommendations. In QueryTogether, most entities mentioned as part of a conversation were readily available as search objects that could directly be used in search without resorting to typing. Our system's novel features allowed us to obtain an environment effectively supporting the spontaneity of ubiquitous scenarios typical of our vision with the more effective usage of heterogeneous devices, a more flexible change of working style, and better search engagement. Moreover, QueryTogether supported effective collaboration through more balanced participation and by creating opportunities for common ground establishment. While there are still many open challenges regarding support for multi-device search in ubiquitous settings, our work highlights the benefit of interfaces based on entity-centric exploration and uncovers design opportunities for future developments of the approach.

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Supplementary material

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