CoScribe: Integrating Paper and Digital Documents for Collaborative Knowledge Work

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Abstract—This paper presents CoScribe, a concept and prototype system for the combined work with printed and digital documents, which supports a large variety of knowledge work settings. It integrates novel pen-and-paper-based interaction techniques that enable users to collaboratively annotate, link and tag both printed and digital documents. CoScribe provides for a very seamless integration of paper with the digital world, as the same digital pen and the same interactions can be used on paper and displays. As our second contribution, we present empirical results of three field studies on learning at universities. These motivated the design of CoScribe and were abstracted to a generic framework for the design of intuitive pen-and-paper user interfaces. The resulting interaction design comprising collaboration support and multiuser visualizations has been implemented and evaluated in user studies. The results indicate that CoScribe imposes only minimal overhead on traditional annotation processes and provides for a more efficient structuring and retrieval of documents.

Index Terms—Collaborative learning, computer-supported cooperative work, paper interfaces, digital pen, input devices and strategies, hypertext navigation.

1 Introduction

Despite the advances in computing, traditional paper is still widely used in learning and knowledge work. For instance, most learners prefer printing their documents for reading, even if these are available online. Research shows that, particularly for reading, paper has inherent advantages over digital documents (e.g., [32], [1], [28]). To state only some of them, annotating paper documents with a pen is intuitive, very flexible, and smoothly integrated with reading. Moreover, paper provides for two-handed interaction and navigation and for creating flexible spatial arrangements.

Most current learning technologies do not account for this paper-centric practice and focus on a complete digitization of learning contents, activities, and communication. In contrast, our approach combines the advantages of paper and digital support.

The main contribution of this paper is CoScribe, a concept and prototype system for paper-centric learning and knowledge work. Learners use the same digital pen to interact both with printed documents on paper and digital documents on a tabletop display (Fig. 1a). This leads to a very seamless integration of both worlds. CoScribe includes novel interaction concepts which support three central activities of learning with documents: It enables users to collaboratively annotate printed and digital documents, to relate documents with hyperlinks and to abstract from contents to higher level concepts with tags. These are important activities in learning, for example, for taking notes during courses, for reviewing them later on as well as for systematizing and integrating literature. Taking notes stimulates students to actively read a document or follow a course and to rephrase contents in their own words. By abstracting and establishing relationships between concepts, learners build structural knowledge, which facilitates recall and comprehension and is essential to problem solving [13]. Finally, CoScribe supports both colocated and remote asynchronous collaboration, enabling learners to construct a shared understanding with others.

Our research was performed in an iterative process. In each cycle, we conducted field studies, derived or refined interaction techniques, implemented these, and evaluated them in user studies. Accordingly, results of empirical studies represent the second contribution of this paper.

In an inductive empirical process, we further abstracted these findings to a theoretical framework for pen-and-paper user interfaces. This framework, our third contribution, provides general guidelines on how to design simple and intuitive paper-based interfaces.

The remainder of this paper is organized as follows: We first motivate the design of CoScribe by discussing main findings both of related research on document use and three own field studies. After reviewing related work, we introduce an interaction framework for pen-and-paper user interfaces, which forms the basis of our design. Then, we present CoScribe and contribute novel pen-and-paper interaction techniques for annotating, linking, and tagging documents. Finally, we discuss implementation issues and present results of an evaluation.

2 Motivation: Field Studies on Learning with Documents

In order to motivate the design of CoScribe, we examined document usage, notetaking, and annotation practice in

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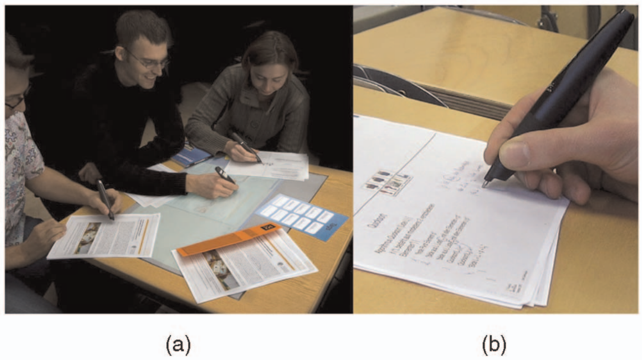

Fig. 1. CoScribe supports a variety of settings, including (a) colocated collaboration and (b) mobile individual work.

university learning. We took into account findings from the literature and conducted three field studies.

2.1 Annotation and Notetaking in Courses

2.1.1 Preference of Paper

Empirical studies [1], [28], [32] show that knowledge workers frequently prefer paper to digital media for reading and writing. Using paper has advantages for annotating, navigating, and cross-document use. As most often reading co-occurs with some kind of writing [1], notes and annotations are an important part of reading processes. In contrast to typewritten notes, handwritten notes and annotations are very easy and intuitive to make and can be more smoothly integrated with reading [28]. In addition to pure text, they can consist of graphical contents, such as underlinings, formulae, or sketches, and therefore, support highly individual notetaking styles [23]. Moreover, users can quickly navigate through a paper document using both hands for searching and skimming and for sensing the appropriate number of remaining pages [32]. Finally, several printed documents can be laid out in the physical space, e.g., for getting an overview, for comparing pages, and for creating cross references [28].

As these studies focus on workplace reading and not on learning at universities, and moreover, do not provide quantitative data on the use of paper and digital media, we conducted own field studies. We will now summarize main results. Details can be found elsewhere [34], [35].

Our first study focused on the notetaking behavior of students in university lectures. We assessed which media are used for taking notes and what are the (dis)advantages of those media. It was a quantitative questionnaire-based investigation with 408 students (290 males and 118 females) enrolled in computer science and pedagogy. A large majority indicated to use only paper for taking notes (77 percent in computer science; 92 percent in pedagogy). Only a very small fraction reported to exclusively use a laptop (8 percent in computer science; 1 percent in pedagogy). This is true despite the fact that 78.6 percent of the students owned a laptop. Participants indicated as most important factors the ease and flexibility of handwritten notes (computer science students often make sketches and drawings during the lecture) and the mobility of paper. While the differences between computer science and pedagogy students let us assume that more training leads to a higher use of laptops, paper is still largely preferred even by computer science students. Despite this clear preference of paper, computer science students frequently use digital media as well. They frequently look up information on the Web ($\mathrm{M} = 3.8$ on a five-point scale, $\mathrm{SD} = 1.0$, and $\mathrm{N} = 305$) and view recordings of the lecture ($\mathrm{M} = 3.2$, $\mathrm{SD} = 1.5$, and $\mathrm{N} = 118$).

In a second field study, we analyzed 1,393 annotations that 24 postgraduate students made on presentation slides during nine sessions of a university seminar. Each participant could choose between using either traditional pen and paper or a tool for making typewritten annotations on a laptop. In average, participants of the laptop group made significantly less annotations per participant and session ($\mathrm{M} = 8.9, \mathrm{SD} = 6.0$) than those of the paper group ($\mathrm{M} = 19.9, \mathrm{SD} = 12.1; \mathrm{T}(22) = -2.6, \mathrm{p} = 0.015$). The large variance within the groups shows that the annotation style is highly individual.

2.1.2 Semantic Tagging

Our findings show that students use specific classification schemes to classify document contents for later retrieval. In order to do so, participants marked up slides with question and/or exclamation marks (76 percent of the participants) and with other personally defined symbols or abbreviations (43 percent of the participants). We manually analyzed 1,081 handwritten annotations and found that an important proportion of 11 percent of them acted as classification markers containing nothing but one of these symbols or abbreviations.

2.2 Document Use in Learning Group Meetings

The two previous studies provided quantitative insights into the annotation and notetaking behavior on individual documents. Our third, ethnographic study focused on the relations between multiple documents and multiple users during learning group meetings. The goal of this study was to find out which document types are frequently used, to analyze the functional roles of these documents and explore how participants interact with documents and with each other. For this study, we observed 12 groups working in publicly accessible spaces at our university. Each observation lasted between 45 and 90 minutes and was followed by a group interview.

2.2.1 Various Types of Media

All groups used printed scripts and empty sheets of paper. Several groups, moreover, used books and file cards. About half of the groups used electronic documents displayed on up to three laptops. These were PDF documents, Web pages, and source code for programming tasks.

2.2.2 Cross-Document Use

Most groups covered the available table surface to a high degree with documents (Fig. 2). The use of these multiple documents was tightly interwoven, whereby each document had a specific function. The task of understanding a particular problem can, for example, include reading a slide of the course script on the screen of a laptop, making simultaneously a sketch on scratch paper, and then, formulating a summary in a paper notebook. Three main functions of documents that we identified were: 1) being a

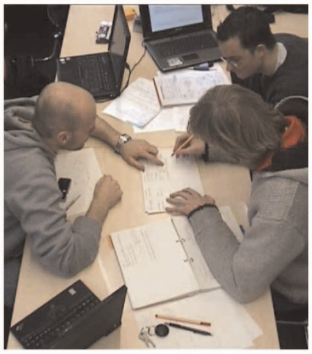

Fig. 2. Document use in a typical learning group meeting.

source providing input to discuss, 2) being a medium for the externalization of thoughts, and 3) being a guideline for the sequential structuring of the topics to discuss in the meeting. As these documents contribute to the same learning tasks, they form an interconnected document space that is collaboratively used by several learners.

2.2.3 Collaboration

All learning groups clearly distinguished personal from shared documents. They used implicit social protocols for conveying the status of a document. This was typically done by positioning personal documents in one's personal attention space and centering shared documents between two or more persons. While the participants pointed very frequently to documents of other group members (mostly to documents of the person directly addressed when speaking), they never wrote on these documents. Although personal documents may become a temporary focus of collaborative work (e.g., several persons reading and pointing to the same document), our observations show that their personal status is maintained. Three groups used explicit shared documents (scratch paper and handwritten summaries) which equally belonged to all group members.

2.3 Implications

The finding that several learners collaboratively work with a single interconnected workspace lead us to applying an *ecological perspective* as our guiding theory. This perspective, which surpasses the individual user-individual document view, follows the concepts of Information Ecologies [25] and Distributed Cognition [11]. Both theories commonly advocate an integral view on the interplay of collaborating users, physical and digital artifacts, and work practices. They argue that this ecological perspective is the key for understanding and supporting knowledge work in a given collaborative context. Based on this perspective and the findings presented above, we inferred the following requirements for an interaction design which supports collaborative learning with documents.

2.3.1 Support of Both Printed and Digital Documents

We have seen that both printed and digital documents are typical artifacts in information ecologies. The design should therefore integrate printed with digital documents and support the digital interaction with printed documents. In addition, it shall support similar interactions with digital documents. This enables users to choose the adequate medium for a given task.

2.3.2 Annotating, Linking, and Tagging

We identify three main conceptual activities to be supported in learning with documents. First, the design shall enable users to make handwritten annotations on documents. Accounting for the highly individual annotation style, the paper-based user interface should impose as little constraints as possible on the flexible interaction with paper documents. Moreover, we have discussed that often multiple documents are tightly interwoven. In order to let the user express these relations, the system shall support creating and following own hyperlinks. To further integrate multiple documents, to structure the learning domain, and to account for existing practices of semantic tagging, the design shall offer the possibility to tag documents with semantic concepts.

2.3.3 Collaboration

The design should support the various forms of collaboration that exist in university learning. This includes colocated collaboration, for example, in learning group meetings, and remote collaboration.

3 Related Work

In this section, we review related research that aims at supporting knowledge workers in annotating, linking, and tagging documents. Research can be divided into three categories following the interaction devices used: 1) traditional interaction with a keyboard and a mouse, 2) imitating paper with pen-sensitive displays, and 3) using real paper. A further dimension of our review is how collaboration is supported.

3.1 Traditional Interaction

Extending and categorizing documents with annotations, links, and tags is supported by a considerable number of systems. Word processors and document viewers contain functionality for annotating documents, which is widely used. Moreover, with the advance of Web 2.0, it became common to create hyperlinks between existing Web documents (e.g., in Wikis) and collaboratively tag these documents. In contrast, tools for annotating Web pages exist but are still less common.

In contrast to our approach, all these systems require a keyboard for writing. This does not integrate well with active reading processes, i.e., reading which is interwoven with taking notes [32]. Using a pen to make handwritten notes and annotations on the document is more intuitive and direct, quicker, and more flexible.

3.2 Pen-Based Interaction

XLibris [31], [29] is a device similar to an eBook reader which enables the user to create handwritten annotations as well as hyperlinks between documents on a pen-sensitive display. In contrast to CoScribe, it does not support collaboration. Collaboration is provided by classroom annotation systems. Using pen-sensitive displays, students can annotate lecture slides [2], [5], [7] or audiovisual lecture recordings [14], [17], [37]. Notes can be digitally shared with other students or sent to the instructor. While most of these systems are research prototypes, two of them [2], [5] reached production stage and are broadly deployed.

While pen-sensitive displays, e.g., in Tablet PCs, maintain to some extent the ease-of-use of pen and paper, they cannot imitate all advantages of paper, e.g., the concurrent use of multiple pages and their flexible spatial layout. This is supported by CoScribe, which uses real paper.

3.3 Interacting with Real Paper

3.3.1 Technology

Technology for capturing pen input on real paper should offer high tracking performance while restricting the natural interaction as little as possible. A first class of approaches tracks the position of a stylus on a fixed surface using a separate tracking device. Examples of this device include a graphics tablet which is positioned underneath the paper document or a device that detects ultrasound emitted by the pen. However, these devices cannot detect the pen position on a sheet of paper but only its position on the surface. Therefore, the position of each sheet must be manually calibrated and sheets must not be moved after calibration. Using a camera as the tracking device, which is mounted above or in front of the surface, solves this problem, as it can also track the location of the paper sheets. Nevertheless, interactions are still restricted to a rather small area in front of the camera.

In contrast, pen-based capturing does not require external devices besides the pen. The commercial Anoto technology is the currently most advanced solution. Anoto pens behave like ordinary ballpens and leave visible ink traces on paper. In addition, a built-in camera decodes positional information from a nearly invisible dot pattern which is printed on the paper sheets. Users can naturally work with multiple sheets of paper without calibration. Data are transferred to a computer via Bluetooth or USB. Recent research demonstrated how Anoto pens can also be used for pen input on rear-projection screens [6].

3.3.2 Notetaking and Annotation

Augmented paper notebooks [21], [36], [41] enable users to make handwritten notes on empty paper (but not on printed documents) and access a digital copy of them in a document viewer. Annotations on printed documents are supported by PADD [10] and PaperPoint [33], which automatically add all annotations to the digital version of the document. In contrast to CoScribe, no functionality for sharing annotations is offered. Synchronous sharing of handwritten notes is supported by PaperCP [19] and AirTransNote [24]: Students can electronically send notes or annotations made on paper to the teacher or to the group. All these systems print documents in one fix layout. While borrowing the idea of paper-based annotation, we focus on a user-adaptable printed user interface and the asynchronous sharing of handwritings.

3.3.3 Hyperlinking and Tagging

Books with Voices [15], Print-n-Link [26], and the seminal Digital Desk [39], [30] allow users to follow predefined hyperlinks from printed to digital documents by selecting a link hot spot on paper. Other systems [3], [16], [40] additionally support users in creating own links, but they are also limited to links from paper to digital media. PapierCraft [20] is more versatile and offers a rich set of pen gestures for links in any direction. Moreover, the user can tag documents or passages with predefined categories and freely chosen handwritten labels. However, the system relies on a large number of rather technical pen gestures, which are different from established practices. Moreover, the pen gestures require an additional device for switching between a writing and a command mode. DocuDesk [8] supports creating many-to-many links between printed and digital documents that are positioned on a pen-sensitive display. While the pen-based interaction for creating links is very intuitive, links always apply to entire documents and paper documents must be kept flat and within the surface of a 22 inch screen. In contrast to our approach, all these systems except for the Digital Desk require separate devices for interacting with paper and digital documents. They, moreover, do not support sharing links.

3.3.4 Frameworks for Paper-Centric Interaction

Research on paper-centric interaction almost exclusively focused on developing new systems. Little work has adopted a more general and theoretical perspective. Yeh et al. [42] define a design space of paper interactions and present a toolkit for the rapid development of PPUIs. However, the underlying interaction model covers only interactions with single sheets of paper. Liao et al. [18] analyze the design space of pen-based feedback mechanisms in paper-only environments. Holman et al. [12] present base units for interacting with digital paper displays. In contrast to our work, these focus on interacting with the hands and not with a pen. The iPaper framework [27] presents an extensive model for links between physical and digital documents, but does not cover interaction techniques.

4 Framework for Pen-and-Paper Interaction

A key question of our research is how to design pen-and-paper interactions that are intuitive and efficient. In this section, we present an analytical perspective on paper-based interaction which provides guidance for the design of paper-based user interfaces. The framework was designed in an inductive empirical process. It is grounded on our ethnographic work and an analysis of existing user interfaces from related work. It is the foundation of the interaction design of CoScribe.

We will use the term *Pen-and-Paper User Interface (PPUI)* to refer to digital interaction with paper documents. The main interaction device in PPUIs is a digital pen, which is used to write on real paper. The pen transfers digital ink (e.g., handwriting, drawings) as well as additional interactional information (e.g., pen "clicks" on virtual paper buttons) to a computer.

Pen-and-Paper User Interfaces have other characteristics than Graphical User Interfaces (GUIs), as they are of a physical nature. Moreover, paper is a very restricted output channel, which makes it challenging to design a UI that is reliable even when no or very restricted system feedback can be provided. This implies that it is not sufficient to simply transfer GUI interactions to pen and paper. We

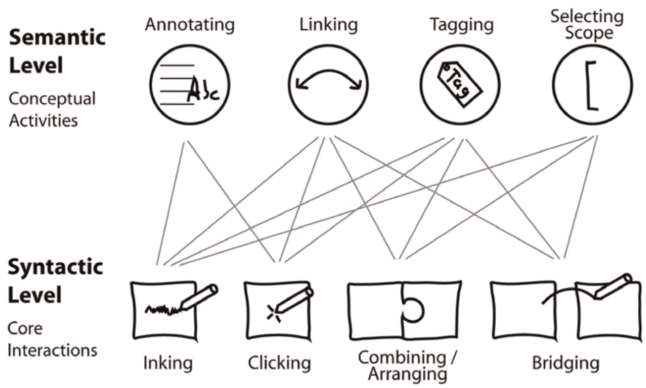

Fig. 3. Applying the framework for CoScribe's interaction design.

argue that instead, interactions should build upon specific affordances of pen and paper.

4.1 Semantic and Syntactic Levels of Interaction

Our approach for designing PPUIs is to let the user fully maintain her existing practices of working with a pen and printed documents. This accounts for the highly individual practices observed in contextual inquiries. However, while the system is able to store and display these informal artifacts made by the user, it cannot interpret them. If the user wants to inform the system about the semantics of the artifacts, she additionally performs more formal actions. These have to be simple, quick, and reliable to be easily integrated into the work process without producing significant extraneous cognitive load.

For this purpose, the framework analytically separates two levels: The semantic level models *what* the user wants to do and comprises *conceptual activities* (for instance, the activities of annotating, linking, and tagging). The syntactic level models *how* the user actually performs these activities. It comprises *core interactions*, i.e., primitive manipulations made with the PPUI.

The challenge when designing a PPUI is first to identify simple and reliable core interactions which leverage the affordances of pen and paper. Second, the designer must decide which core interactions to use and how the user combines them to perform a conceptual activity. Ethnographic observations of users' current practices are an important method for informing these design decisions.

4.2 Semantic Level: Conceptual Activities

The semantic level comprises the conceptual activities which are offered by the PPUI. CoScribe supports four main activities. These are annotating, linking, and tagging (Fig. 3, upper level). Moreover, users can select the scope of an annotation, link, or tag. This is, for instance, a passage within a document or a collection of several documents.

Conceptual activities can be hierarchically organized. For instance, scope selection is a subactivity of the three other activities. We might also define higher level activities. For example, CoScribe supports "excerpting on a separate sheet of paper," which relies both on annotation and linking.

4.3 Syntactic Level: Core Interactions

We now discuss which core interactions are used to support these conceptual activities. A core interaction is defined as

TABLE 1
Comparison of Core Interactions

	Traditional Paper	GUI (foll. [4])	PPUI
Single sheet	Writing	Text entry	Inking
	Pointing	Pointing/ Clicking	Clicking
	(Moving	Dragging	Moving)
	(Altering shape	--*	Altering shape)
Multiple sheets	Arranging and Combining	--*	Combining
	Subsequent pointing	--*	Bridging

** No core interaction (performed by combining several core interactions).*

an operation that a user performs by manipulating one or more page areas using his or her hands and/or a digital pen. Page areas comprise, for example, a document page, a printed "button," or a paper sticker. Depending on the type of page area, it is performed on, a core interaction can have different meanings.

CoScribe relies on the following core interactions which are performed with a single sheet of paper (Fig. 3):

- **Inking**: Writing with the digital pen on a page area. This includes handwritings and drawings that are not interpreted by the system. Specific symbols and pen gestures may be interpreted to issue a command.
- **Clicking**: Performing one or more pen taps on a paper area to issue a command (e.g., on a printed "button"). This is inspired by pointing gestures. While inking leaves visible pen traces and permanently alters the document, clicking is volatile, leaving it unchanged.

An important characteristic of paper is that it affords using several sheets of paper at a time.

- **Combining**: Creating or modifying arrangements of page areas. This may be rather volatile (e.g., paper sheets laid out on a desk) or rather permanent (e.g., attached paper stickers, documents filed in a folder).
- **Bridging**: In contrast to physical combinations, bridging is a *logical* combination of several areas. This complements physical combinations or substitutes them when these are impractical or impossible. Inspired by consecutive pointing on several items, we model bridging as a connecting pen gesture on two areas.

We identified two further core interactions, which, however, are not used in CoScribe. These are *moving individual pages* without relation to others (substituted by combining, as cognitive activities typically consist of creating or modifying arrangements) and *altering the physical shape* of a page, for example, by bending, folding, or tearing it.

Table 1 depicts how the core interactions are inspired by interactions with traditional paper and how they correspond to GUI interactions. PPUIs should account for the rich interactions that are possible with paper. Table 1 shows that the interactions which leverage the physical specifics of paper environments go beyond interactions in GUIs. Hence, by merely mimicking GUI concepts, one would considerably reduce the richness of the interaction. Instead, the design should focus on core interactions that imply the simultaneous use of multiple sheets.

In Fig. 3, the edges between the upper and the lower level show how the design of CoScribe maps core interactions to conceptual activities. This indicates that core interactions are flexible building blocks which are used and reused for multiple conceptual activities. In the next sections, we present CoScribe and its interaction techniques.

5 Overview of CoScribe

CoScribe is a concept and system which supports knowledge workers in working with printed and digital documents. A tight coupling of printed and digital documents must both bridge the gap between different *interactions* in both worlds and integrate the *contents* contained in printed and digital media. Our approach accounts for both these levels.

First, CoScribe provides unified pen-based interaction techniques for annotating, linking, and tagging both printed and digital documents. These techniques leverage the ease and flexibility of interacting with real paper and enhance these with digital support.

Learners can print digital documents onto real paper and interact with them using a digital Anoto pen. Changes made on a printed document are automatically included in its digital version and available in the CoScribe viewer. In addition to printed documents, CoScribe offers various specialized tools made of paper (such as folders and index stickers). With a print tool, the user can easily print documents and paper tools using an ordinary printer. As the main functionality only requires a digital pen and paper, CoScribe supports mobile use and allows, for instance, to read and annotate documents in the lecture hall, at home, or in public transport.

Moreover, the same digital pen can also be used on an interactive table to work with digital documents. Currently, supported document types are PDF and PowerPoint, Web pages, and physical books.

Second, CoScribe helps the knowledge worker in integrating the contents of printed and digital documents. Our field studies have shown that learners typically work with an interwoven set of documents, where information is distributed between several printed and digital documents (e.g., between a printed lecture script, some additional Web pages, and a personal notebook). Today, these relations often remain implicit, which makes it difficult to quickly access related documents and share this information with other learners. In order to structure and work with a mixed physical and digital collection of documents, CoScribe enables learners to add and follow own hyperlinks between documents and to tag documents. During active reading or when users integrate information, annotating, linking, and tagging are typically tightly interwoven.

CoScribe further supports collaboration around printed and digital documents. Several users can collaborate at the same place, each having an own digital pen. Moreover, users can share annotations, links, and tags over the distance. In this case, CoScribe supports large groups (e.g., several hundreds of persons in a lecture).

Due to the generic character of annotating, linking, and tagging, CoScribe supports various knowledge work settings. In our application scenario of learning at universities, this includes taking notes and making annotations during courses, reviewing own notes and shared notes of other learners, preparing for exams in learning group meetings, excerpting documents, searching and integrating literature for preparing an article or a term paper, and even giving presentations. All these settings include working with existing documents. In contrast, composing new documents is not the focus of CoScribe, as most often, this is more efficient using a keyboard and a screen than pen and paper. Despite its wide applicability, CoScribe remains easy to use, as it relies on a small set of simple and reliable interactions, which are inspired from traditional practices of working with paper documents. In the following sections, we will present CoScribe in more detail.

6 Annotating Documents

While it is very easy and intuitive to annotate documents with a traditional pen and paper, this has also several shortcomings: the static layout of printouts might provide too little space for extensive annotations, annotations on paper are hard to share over the distance, and the user must switch between different input devices for paper and digital media. We now discuss how CoScribe's annotation interface addresses these issues.

6.1 Pen-Based Annotation

6.1.1 Unified Interaction with Physical and Digital Documents

With a digital Anoto pen, the user makes handwritten annotations at any position on printed documents. The pen data are either sent in real time to a nearby computer or remains on the pen until it is synchronized. Once the data are transferred to a computer, it is stored in a central database and digital versions of the annotations are available in the CoScribe viewer (Fig. 4).

This viewer allows to make handwritten annotations on the digital version of the document. We therefore developed a specific display which supports input with one or several Anoto pens. It can be used as a tabletop display or as a vertical screen (see Section 9 for more details). The viewer is tightly coupled with printed documents, as the user can quickly access the digital version of each printed document page by tapping with the pen on a button which is printed on each page.

6.1.2 Flexible Printed User Interface

As Marshall [23] points out, users have highly individual annotation styles. The printed user interface was therefore designed to constrain the personal annotation style as little as possible. The interface can be customized both at print time and during use later on. To the best of our knowledge, related work on paper-based user interfaces does not address this issue.

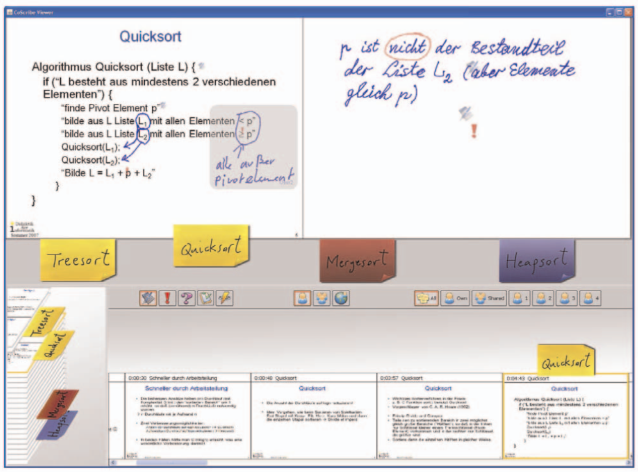

Fig. 4. The CoScribe viewer for printed documents provides access to one's own annotations (handwriting) and shared annotations of others (symbols). A shared annotation is expanded (annotation with gray background) by hovering over or tapping on its symbol.

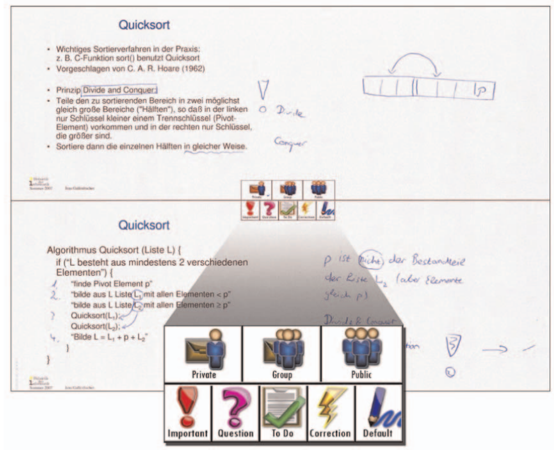

Fig. 5. Example layout of printed lecture slides including additional notetaking areas. A printed toolbar (enlarged) provides for classifying annotations with a visibility level and semantic categories.

A printout module allows to print documents in various layouts. For instance, several document pages can be printed on one single sheet of paper and empty areas for longer notes can be optionally included (Fig. 5). This provides for an adaptation to user preferences (e.g., left handers versus right handers) and the context (e.g., annotating lecture slides versus excerpting on a separate sheet of paper). A printout can optionally include own or shared annotations which were previously made. In addition to this static customization of the print layout, users can create hyperlinks to dynamically add further empty paper sheets when more space is needed (see Section 7).

6.2 Collaboration

6.2.1 Colocated Collaboration

Several learners can use the system at the same time in the same place, e.g., in a group meeting, and interact with personal and shared, printed, and digital documents. In this case, several pens connect to one computer.

CoScribe supports the colocated use by several persons better than ordinary computers for two reasons. First, users do not need to share a single input device, as each user has a personal digital pen. This, moreover, allows attributing the activities to individual users. Second, enough interaction space is available for independent activities of several users: Interactions are not restricted to one single point of focus but can be made on different documents located at various physical places.

6.2.2 Remote Sharing of Annotations

Moreover, CoScribe supports asynchronous collaboration over the distance. It enables users to share their annotations with each other over a network connection. Coworkers can access shared annotations in their CoScribe viewers. This enables students to critically examine their own notes and verify their understanding of the learning matter by comparing with annotations of others.

An important aspect about sharing of annotations is privacy. For this purpose, collaborative paper-based annotation systems should provide a means for defining the visibility of annotations on paper. Related research [19], [20] discusses three mechanisms: Spatial differentiation requires separate areas for different levels of visibility, which is clearly impractical for annotations. Using a different pen for each level is intuitive but requires extra hardware. Moreover, students tend to use one single pen rather than switching between many tools [22]. A third approach, drawing different symbols, requires live feedback on the success or failure of symbol recognition. Current pens cannot provide this without a nearby computer.

We therefore propose a fourth concept: button-based differentiation. Three buttons (Fig. 5), printed on each paper sheet, provide for a quick and easy means for defining an individual annotation either as private, as visible to members of the user's learning group (set up with several other learners), or as visible to all users. A visibility level is assigned by consecutively tapping with the pen on the corresponding button and the annotation. This interaction can be recognized without uncertainty and is very reliable. Defining a visibility is optional, allowing the user to maintain a natural annotation style. The same interaction is used for categorizing annotations with semantic types (Fig. 5). A drawback is that the visibility and type of an annotation is not directly visible on paper unless the user makes an extra marking. However, these are visualized with specific colors in the CoScribe viewer and subsequent printouts of the document.

6.2.3 Collaborative Visualization

The CoScribe viewer provides access to both own and shared annotations. A challenge with shared handwritten annotations is their clearly arranged visualization, particularly for a large number of users. By separating the annotations of different users into different views, each of these views in itself becomes easier to read. In the CoScribe viewer, users can manually switch between different *single-user views* for each member of the user's learning group. Yet, this switching becomes particularly cumbersome in larger communities.

Therefore, we developed a novel visualization of collaborative handwritten annotations. An integrated *multiuser view* displays both one's own and shared annotations in an integrated manner. This supports overview of and access to shared annotations without the need of switching between different views. Accounting for the restricted space within the document, one's own annotations are visualized as they are written on paper, whereas shared comments of other users are displayed in a condensed form. Instead of the annotation itself, a small icon is visualized at the position of the annotation (Fig. 4, upper right). This icon corresponds to the annotation category and varies in size according to the size of the annotation. When hovering with the mouse over the icon or tapping with the pen, the annotation is expanded and displayed at the correct position in its original size (Fig. 4, annotation with gray background). Shared annotations considered particularly relevant can be added to the own script and are permanently expanded. In contrast to moving overlapping annotations to other positions, condensing and expanding keeps them at their correct position on the document. This is important if the annotation graphically refers to the document (e.g., underlinings or corrections).

Summing up, annotations can be made very easily by just writing with the pen and optionally tapping on a button for defining visibilities and categories. Shared annotations of other users are available in the CoScribe viewer and can be included in subsequent printouts.

6.3 Handwriting Recognition

A substantial advantage of digital over traditional handwritings is the possibility to recognize the handwritten text and offer full text search. Yet, the accuracy of the recognition of free form annotations is low. We used the Microsoft Vista Handwriting Recognition Engine to evaluate recognition accuracy on 169 handwritten annotations made on lecture slides by students attending these lectures. The resulting word and character error rates elevated at 49.2 and 18.6 percent, respectively. A manual analysis showed that in contrast to handwritten notes on empty pages, annotations heavily varied in size, position, and orientation. They often contained mixed text and drawings, abbreviations as well as domain-specific terms (like "$O(n \log n)$") or formulae. We could reduce the word error rate for domain-specific terms by 19.4 percent. We therefore added all tokens from the slide the annotation was made on as well as tokens from the five preceding and following slides to the dictionary of the recognition engine. This can improve full text search for domain-specific terms. However, due to the low accuracy, the interaction design of CoScribe does not require handwriting recognition.

7 Linking Documents

Learners can create and follow own hyperlinks between existing documents in order to connect contents of printed and digital documents in any combination.

A hyperlink is modeled as a symmetric binary association between 1) collections of documents, 2) entire documents, and 3) rectangular areas in the same or different document. While we model document passages as a region of space, our interaction design could be coupled with the automatic extraction of document elements [38]. This would provide for linking specific semantic objects of the document.

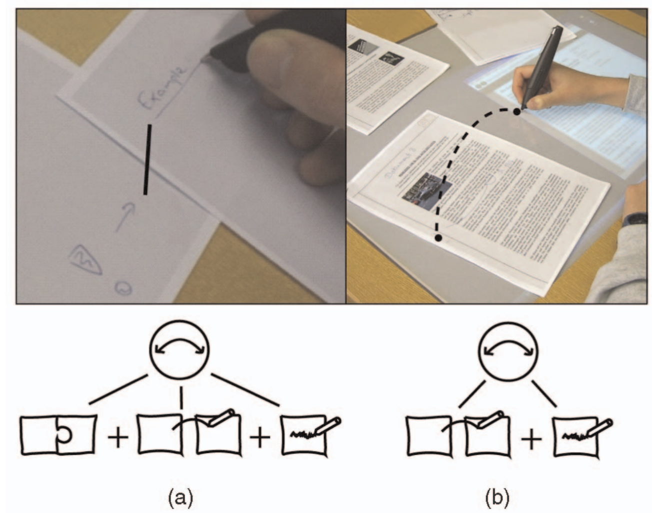

Fig. 6. Creating hyperlinks with pen gestures. The lower part depicts how the interactions fit into the framework. (a) Single-line gesture. (b) Two-part gesture.

7.1 Creating Hyperlinks

7.1.1 Association Gesture

Accounting for the associative character of hyperlinks, the interaction for creating links is a pen-based association gesture, which connects both link anchors. In order to create a new hyperlink, the user arranges both documents to overlap and connects both link anchors by drawing a line (Fig. 6a). As an alternative, the user makes two consecutive pen taps on both link anchors (Fig. 6b). The gestures can span paper and the pen-enabled display. In order to be able to follow links without computer, the user can optionally add handwritten, human-readable references. These are not interpreted by the system.

As both gestures can be reliably recognized, they can be used even in mobile settings when no computer feedback is available. If a computer is nearby, it gives instant audio feedback. A link can be deleted with a cross-out gesture on any marking made for creating this link.

7.1.2 Link Scope

It is established practice to create references to passages of different extent. This includes referencing an individual figure or a short paragraph, entire pages or chapters, and a whole book or even several documents. CoScribe provides an easy means for flexibly defining the scope of a link anchor. Depending on the area the association gesture is performed upon, the link has a different scope.

If the association gesture is performed on the upper part of the first page of a document, the link applies to the *entire document*. Links from and to *subpassages* are made in the margin besides this passage. By optionally drawing a vertical line, the extent of this passage is precisely defined. *Collections of documents* are defined by placing physical documents into a folder (Fig. 7b). Digital documents can be virtually added. Association gestures made on the front flap of the folder, then create a link from and to all these documents. Finally, links can apply to ordinary *physical books*. For this purpose, users can attach a small sticker onto

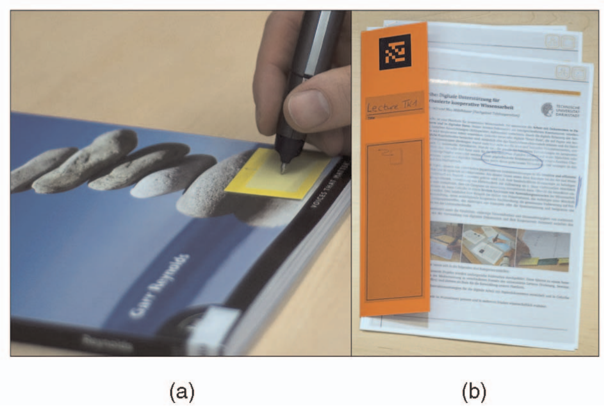

Fig. 7. Creating links on (a) books and (b) document collections.

the book cover where the pen gesture is made (Fig. 7a) and register this sticker with the book's barcode. Metadata of the book and an image of its cover are automatically retrieved via the Amazon.com web service.

7.2 Following Hyperlinks

A hyperlink is followed by tapping on or near a link marking (gesture or human-readable reference) (Fig. 8). This is possible on a printed document page, a digital document on the display, a book, and a folder cover. The target document is then displayed either in the Web browser or in the CoScribe viewer.

7.3 Ecology Visualization

Views of individual documents provide only a very restricted overview on how a collection of documents is interconnected by hyperlinks. Therefore, CoScribe provides a higher level view that visualizes the entire information ecology. Its focus is on the relations between documents and the activities that users performed on these documents. It supports collaboration, as all links and tags of all users are integrated into one view.

Due to the focus on relations, we opted for an interactive graph visualization (Fig. 9). Nodes of this graph are thumbnail representations of documents, books, folders, tags, and users. Links, tags, and activities of users are represented by the edges. If a document contains more than one page, its node can be unfolded to display the individual pages. The same applies to folders. The view is closely

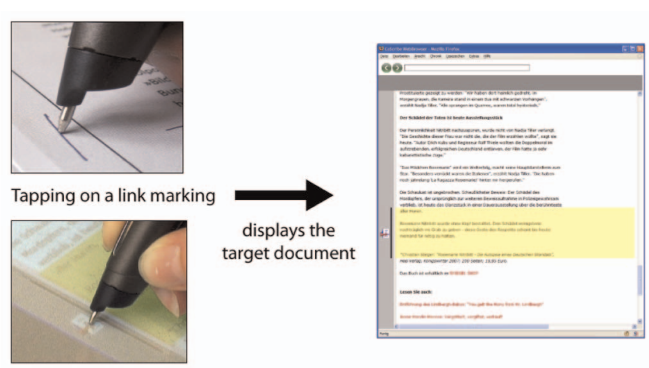

Fig. 8. Following links on paper and the pen-enabled display.

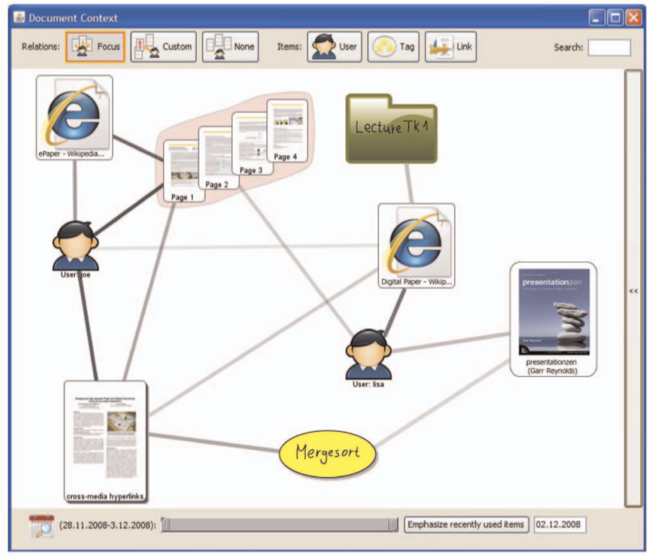

Fig. 9. Ecology visualization of relations between documents, tags, and users.

coupled both with paper and the document viewer. Comprehensive filter options (including time, specific tags, and users) can be easily manipulated to focus on specific aspects of the possibly large graph.

8 Tagging Documents

A third important aspect besides annotating and linking is tagging document contents with a keyword or a semantic category. This supports the important learning processes of structuring documents, identifying relevant concepts of the learning matter, and abstracting to higher level concepts. Later on, the users can easily access relevant document passages in a structured way.

Our model supports *category tagging* with predefined categories as well as *free tagging* with one or several freely chosen keywords. Category tagging has two main advantages: First, the availability of specific categories can support metacognitive learning processes by encouraging and reminding students to perform specific important learning activities. Second, some common semantic classes facilitate the computer interpretation of tags, the sharing with other learners, and automatic aggregations. In contrast, free tagging is more flexible and can be used for a wide variety of purposes, for instance, for recommending contents to a collaborator by tagging them with his or her name or for prioritizing contents.

In the remainder of this section, we will present two interaction techniques that combine physical with digital tagging. These complement each other, serving different purposes and having different properties. Both techniques have in common to be very reliable even in situations where no nearby computer could provide feedback on the success or failure of the command.

8.1 Digital Paper Bookmarks

Paper bookmarks are a well-established and efficient means for structuring documents, marking specific passages on

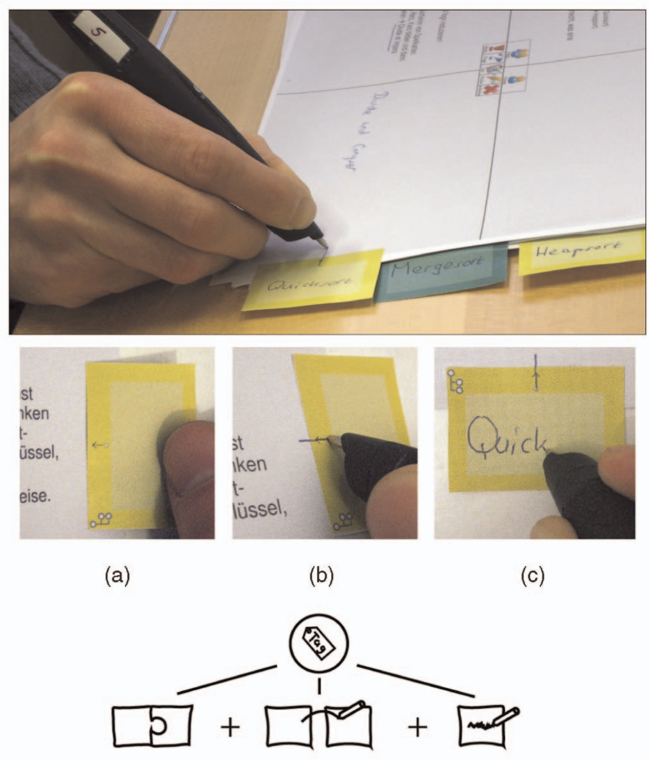

Fig. 10. Interaction for creating a Digital Paper Bookmark. The lower part depicts how the interactions fit into the framework. (a) Combine. (b) Associate. (c) Label.

paper, and quickly accessing them later on. Digital Paper Bookmarks combine the advantages of traditional bookmarking with digital support (Fig. 10).

8.1.1 Interaction

A Digital Paper Bookmark is an adhesive sticker of one of different colors. Learners can easily create Digital Paper Bookmarks via three steps (Fig. 10): 1) First, a bookmark is attached to an arbitrary position of any page of a printed document. 2) Second, it is bridged with this page by drawing a short line connecting the bookmark with the page. 3) It is then also available as a digital bookmark. Finally, since the Anoto dot pattern is printed on the bookmark, learners can use the digital pen to write a keyword on it. The interaction thus combines three core interactions of our framework. The second step is not necessary if technology for tracking the location of paper sheets automatically detects the combination. The manual bridging step lowers the technical requirements and enables bookmarking during mobile use.

This solution for creating bookmarks is highly compatible with existing practices. Since the bookmark is visible on paper, full visual feedback is available without additional digital support. Moreover, its shape provides a strong affordance for quickly accessing the physical page which has been bookmarked. This is a clear advantage over other classification means which do not modify the physical shape of the document.

In addition to free tagging with keywords, Digital Paper Bookmarks offer predefined categories that support learners in structuring documents. Each type is represented by a specific color and a specific symbol.

Fig. 11. A collaborative visualization for comparing the own structuring with those of others. From left to right: Abstracted view of document pages, own bookmarks, shared bookmarks of another member of the learning group, and an aggregated view of all users.

8.1.2 Collaborative Visualization

Once created on paper, Digital Paper Bookmarks are digitally available in the CoScribe viewer and indicate the document's structure. They are visualized directly on the document pages and in a 3D representation of the paper stack (Fig. 4, lower left). Using bookmarks thus automatically creates a personalized index of contents.

An additional collaborative visualization (Fig. 11) aids learners in comparing their structuring of a document with those of other learners. This enables learners to critically examine their own understanding by comparing their own structure with those of other learners. Cognitive conflicts may arise and can lead to a modification of one's mental representation and of the own structuring.

8.2 Tag Menu Card

A second interaction technique for tagging documents relies on one or more separate paper cards, which allow defining and applying keyword-based tags (Fig. 12).

Collecting all tags on a separate Tag Menu Card has the advantage that the user can immediately access a set of all her tags. In addition, Tag Menu Cards support operations on

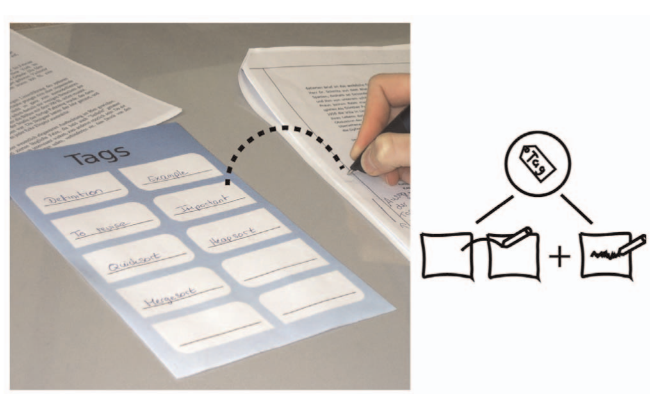

Fig. 12. Tagging a document with the Tag Menu Card.

TABLE 2
Pen-Based Interaction Techniques of CoScribe

	Annotating	Linking	Digital Paper Bookmarks	Tag Menu Card
On printed documents	●	●	●	●
On digital documents	●	●	○	●
Applies to	Page	Folder, Document, Passage	Page	Folder, Document, Passage
Free tagging			●	●
Category tagging			●	○

● = supported; ○ = not supported

the tag set (renaming, etc.), which can then be automatically applied to the electronic representations of all documents and to their subsequent printouts. Moreover, the approach supports colocated collaboration by having users physically sharing cards. Finally, research shows that a key factor for the convergence of tags is that the system suggests frequent labels [9]. Yet, computer support cannot be assumed in a paper-only environment without a nearby display. In such a context, the Tag Menu Card fosters similar effects as the suggestion of frequently used tags: users will be inclined to reusing tags already entered on the card whenever possible, since the effort is lower than making a new tag entry.

8.2.1 Interaction

Each Tag Menu Card contains several empty areas. At any time, the user can define a new tag by writing one or several freely chosen keywords in one of these areas. After a tag is defined, it is applied using either of the following interactions:

1. Writing the tag on a document and enclosing it with a circle in order to mark it as a tag. The tag is automatically recognized from the set of previously defined tags using handwriting recognition.
2. Writing the tag on a document and additionally performing the pen gesture for hyperlinks to bridge it with the corresponding area on the Tag Menu Card. This small additional effort ensures that tagging is correctly performed even when no feedback can be provided, as it does not rely on handwriting recognition.

For faster tagging, the user can print a new version of a Tag Menu Card, in which previously defined tags are ordered and sized according to their frequency (tag cloud). Optionally, tags defined by all users or by members of the own learning group can be included.

8.2.2 Visualization

Tags are displayed both in the viewers for individual documents and in the collaborative context visualization, which integrates documents, links, tags, and users.

To sum up, Table 2 gives a comparative overview of CoScribe's pen-based interaction techniques. Although CoScribe supports a wide variety of activities, the interactions remain simple for the following reasons. First, they are composed of a small set of recurrent core interactions. The user writes with the pen, taps on a button or on a link, or bridges two areas. Each of these interactions is entirely intuitive or very easy to learn. Moreover, CoScribe heavily draws on established practices, such as annotating with a pen or attaching index stickers.

9 Implementation

A prototype system of CoScribe was implemented in Java. It is based on a client/server architecture with a central database, which provides for sharing data with other learners over a network connection.

We use Logitech io2 and Nokia SU-1B Anoto pens. The pen data are transferred via Bluetooth or USB. Pen gestures are recognized by heuristics. Printouts are performed with an OKI C5900 color laser printer. Our prototype uses Microsoft Vista Handwriting Recognition, but the interaction concepts do not rely on handwriting recognition for correct operation, which makes them more reliable.

The backprojection display which supports input with Anoto pens has a diagonal of 82 cm and can be used in a tabletop configuration or as a vertical screen. We constructed it as follows: The Anoto dot pattern was printed onto HP Colorlucent Backlit UV foil, following the approach of [6]. This foil was put between a supporting plexiglass layer of 5 mm width and a protecting ink-repelling layer of 1 mm width. It is illuminated by rear projection with a full HD resolution beamer. As pen data originating from the display are translated to ordinary mouse events, not only our own system can be controlled with the pen, but also all other applications.

10 Evaluation

We conducted a first evaluation of CoScribe with the goal to assess the general concept and gain first user experiences. Three user studies evaluated the use of CoScribe in two central settings of learning at universities: taking and reviewing lecture notes as well as integrating information from a collection of documents. We will discuss each scenario in turn.

10.1 Lecture Notetaking and Review

10.1.1 Study 1: Method

In the first study, we evaluated the printed user interface for making annotations and classifying them in a realistic setting. We opted for three regular computer science lectures of our university. A total of 29 students (five females and 26 males) recruited among the attendees of these lectures participated to this study. Participation was voluntary and no compensation was given. Each participant used the paper interface with a digital pen during one lecture (about 90 min.). Beforehand, he or she was trained for 3 minutes on how to make annotations and classify them. After the lectures, feedback was gathered with a questionnaire and semistructured interviews.

10.1.2 Results and Discussion

Document annotation. Although the users have had only a few minutes for familiarizing with the system and used it

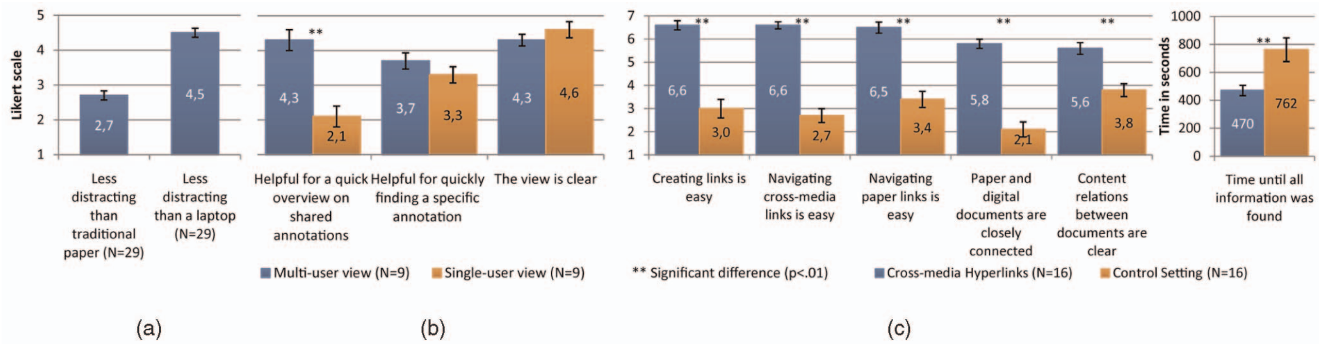

Fig. 13. Main quantitative results. (Error bars show standard error of the mean. All statements are transformed to their positive form.) (a) Paper user interface. (b) Multiuser view. (c) Cross-media hyperlinks.

during one of their normal lectures, they were able to make a considerable amount of annotations. In all three lectures, a total of 1,983 handwritten annotations was made. This results in an average of 68 annotations $(\mathrm{SD} = 29, \mathrm{N} = 29)$ per user during a lecture. The participants were active throughout the entire lecture, each user annotating, on average, 63 percent of all lecture slides.

A substantial percentage of 18.7 percent of the annotations was classified with a semantic category. The most frequently chosen category was "Important" (12.5 percent), followed by "Question" (3.2 percent), "Correction," and "To Do" (1.5 percent each). Tagging with visibilities was performed only for a small percentage of annotations (2.4 percent private and 1.6 percent public). The default setting of group visibility is obviously appropriate for most annotations.

All users reported that annotating printed lecture slides with the digital pen worked reliably and as they had expected. In the questionnaire, the participants judged its use about as distracting as traditional pen and paper, but much less distracting than using a laptop (see Fig. 13a).

The participants had different preferences concerning the layout of printed slides. This underscores the importance of flexible layouts. Three out of four of the participants reported in the interviews to prefer only two slides per paper sheet, as this leaves free areas for annotations. The remaining participants preferred four or more slides per page. All left handers wished having free annotation areas to the left of the printed slides, while right handers preferred them to the right. Positioning the free areas below instead of besides the slides was judged less appropriate, since the items on the slides are typically organized in vertical order.

In the interviews, there was a wide range of responses to the functionality for classifying annotations. While nearly all participants agreed that this is an important feature, that tapping on a button is quick and easy and does not disrupt the main task of annotating, they disagreed about whether the system feedback is sufficient. As the Anoto pens available at the time of the evaluation could not provide system feedback, not all users felt sure that a button has been correctly activated when tapping on it with the pen. Only recently, a novel Anoto pen with a display (Livescribe SmartPen) has been deployed. Using this pen would make the classification more reliable.

10.1.3 Study 2: Method

A second exploratory study assessed the use of CoScribe during review after class, focusing on how shared annotations can be accessed in the different visualizations. Nine students (seven males and two females), recruited among the participants of the first study, participated to single-user sessions, each lasting about 1 hour. No compensation was given. After having the participant shortly introduced in how to use the CoScribe viewer and Digital Paper Bookmarks, we observed her performing given tasks with paper and the CoScribe viewer (reading and annotating, the printed document, accessing shared annotations, and bookmarking). Finally, feedback was gathered with a posthoc questionnaire and a semistructured interview.

10.1.4 Results and Discussion

Reviewing shared annotations. Participants reported in the interviews that to date, handwritten annotations are typically not shared with other students due to the large effort. We asked the participants for what purpose they would use shared notes. Of the variety of answers provided, five users mentioned that they would read the comments made by specific students known to take good notes. Two users stated that notes of different users complement each other, since there is not enough time during a lecture to note all information of importance. Two other users stated to correct own notes with the help of others.

We evaluated the visualization of handwritten annotations. For displaying own annotations, the multiuser view is equivalent to the single-user view because the symbols for shared annotations can be easily hidden. Concerning shared annotations of other users, the participants judged the multiuser view as significantly more helpful when seeking an overview of them $(\mathrm{T}(8) = -5.37, \mathrm{p} = 0.001)$ (Fig. 13b). They also judged this view to be slightly more helpful for finding a specific shared comment (Fig. 13b). We initially feared that the multiuser view would become cluttered, as both own and shared annotations are displayed together. However, participants judged it to be almost as clear as separate views (Fig. 13b). In the interviews, three users stated that a list view of all annotations should complement the view to support users in systematically reviewing all annotations.

Document structuring. The observations of how users create and use bookmarks clearly indicate that the interaction technique is highly intuitive and reliable. All participants readily understood the usage of bookmarks, and created and modified bookmarks without assistance. All interactions were correctly recognized by the system.

10.2 Integrating Information from Printed and Digital Documents

10.2.1 Study 3: Method

In a third study, we evaluated how CoScribe supports users in integrating information that is distributed between several printed and digital documents. We assessed the ease-of-use and the learnability of the interactions for creating and following cross-media hyperlinks as well as the use of the tabletop display. In addition, we had the following hypotheses for the formal experiment:

- H1: The system enables users to perform a complex information retrieval task in a set of interlinked printed and web documents more quickly than with traditional pen and paper.
- H2: Printed and digital documents are perceived as being more closely connected when using cross-media hyperlinks.

A total of 10 psychology and six computer science students (nine females and seven males) participated to 1.5 hour single-user sessions. Participation was voluntary and no compensation was given. They used a digital pen, paper documents, and digital documents on the pen-enabled display. Eight participants used the display in a tabletop configuration, while the remaining eight participants used it as a vertical screen. The sessions were structured as given below.

After 3 minutes of training, the first task of the test persons was to create hyperlinks on a printed document and on Web pages and to follow them.

Their next task was to answer questions on historic murder cases using collections of interlinked printed and Web documents related to these cases. Our goal was to find out if the participants would be able to complete a realistic information integration task more quickly using CoScribe. This task goes far beyond simply following a hyperlink (which obviously takes less time than manually searching the referenced passage). Users had to handle many documents containing not only relevant, but much irrelevant information. Each document collection had 15 to 16 A4 pages mainly consisting of text and three to five Web documents from Wikipedia and online newspaper archives. The relevant information for answering a question was distributed between three and eight passages. Moreover, the users had to decide on the relevance of hyperlinks, since of the eight to 10 hyperlinks per document collection, only about one-third linked to passages which were relevant for a specific question. This setting thus represented a realistic knowledge work task where a coworker had prestructured a collection of documents.

We observed participants navigating within the document collections and measured the time needed until the questions were correctly answered. A within-subject design was used for this experiment. Each participant was trained on a first document set. Two other document sets were then used for testing under either condition (with CoScribe or with printed documents containing handwritten annotations and Web pages containing annotations visualized by the Web annotation tool diigo.com). We counterbalanced the document sets and the order of the two conditions. Finally, we gathered feedback with a posthoc questionnaire and a semistructured interview.

10.2.2 Results and Discussion

Creating and following links. After a few minutes of training, all users had learned how to use the pen on the display and how to create and follow links. Responses to an open question showed that the interaction was appreciated as being "easy" (eight persons), "quick" (two), and "highly intuitive" (two). It was considered very helpful to have the same interaction device for printed and digital documents ($M = 6.4$ on a seven-point Likert scale, $SD = 1.1$, and $N = 16$). Participants reported that this makes the interaction faster and connects printed and digital documents more directly. In the responses to the questionnaire, both creating hyperlinks and following them was judged significantly easier with the system than in the control setting (see Fig. 13c). All but one participant navigated through the interlinked documents with high confidence as if they had been using the system already for a long time.

When comparing the pen-enabled tabletop display with the pen-enabled vertical screen, the tabletop configuration was clearly preferred. Most important reasons mentioned in the interviews were first that it is more natural and ergonomic to use a pen on a horizontal surface, and second that printed and digital documents are more closely coupled using one surface for both of them. However, three participants perceived an extra effort for rearranging documents on the display. This discomfort is due to two deficiencies of our current prototype: the space provided on the tabletop is limited and no provision is made for coping with occlusions of displayed pages.

Performance gain (H1). As depicted in Fig. 13c, completing the task with CoScribe took in average only about 60 percent of the time needed in the control setting. This difference is highly significant ($T(15) = -3.22, p < 0.01$). The main reason for the performance gain was that it takes little time to navigate to the link target, regardless if this is a printed or a digital document. A second speedup factor was that users found more links with CoScribe because all links are symmetric and automatically visible on both endings. In contrast, traditional handwritten references are not automatically visible at the target passage.

We observed that it is very important to label a link anchor with some information about the target document (such as "Biography of the murderer"). While most links were labeled, each document collection contained the same number of unlabeled links. With the latter, the participants were much more likely to get disoriented and be uncertain if they had already followed these links.

Gap between printed and digital documents (H2). With cross-media hyperlinks and the pen-enabled display, the documents are considered significantly more closely connected compared to the control setting (Fig. 13c). The participants also judged the relations between the contents of the different documents to become clearer.

The results of this first evaluation confirm the concept of CoScribe. They show that students accept the system and judge it helpful and easy to use. In order to gain a deeper insight into how learners use CoScribe, we plan to conduct a longer term study in the near future.

11 Conclusion

Highly varied and efficient practices of interacting with physical documents have evolved over hundreds of years.

Compared to these practices, the way we work with documents on today's computers is, in many respects, a step backward. It is therefore an important advance to extend digital interaction from the desktop into the physical space. However, this presents enormous challenges for designing the user interface. We address these by extensive field studies from which we derived a theoretical interaction framework for pen-and-paper interaction. Instead of mimicking interactions of Graphical User Interfaces, the interaction is geared to the varied traditional practices of using pen and paper and leverages the rich interactions that are made possible by combining multiple paper surfaces.

On this basis, we designed CoScribe, an interaction concept and prototypical system for paper-centric knowledge work. Whereas previous solutions supported only a small fraction of the practices which are frequent in typical information ecologies, CoScribe provides more comprehensive functionality: It supports three central and generic activities of working with documents and enables collaboration around the rather static medium of paper. Moreover, CoScribe simplifies pen-based interaction, as the same device can be used for all activities both on paper and displays. Finally, CoScribe creates a richer user experience than previous work by offering a wide set of intuitive tools which are made out of paper.

The results of a first evaluation indicate that the integration of paper and digital documents in a seamless interaction technique and system enhances both work performance and user satisfaction. The interaction techniques can be efficiently utilized even by novices after a few minutes of training.

For the near future, we plan to deploy CoScribe more broadly at our university. As all components except for the tabletop display only require commercially available and affordable hardware, the system can be made available to a large number of users. We envisage conducting further long-term studies that will provide additional insights on how CoScribe affects document use and collaborative practices.

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