AUGMENTED REALITY AND CROSS-DEVICE INTERACTION FOR SEAMLESS INTEGRATION OF PHYSICAL AND DIGITAL SCIENTIFIC PAPERS

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The supervisory committee certifies that this thesis complies with North Dakota State University's regulations and meets the accepted standards for the degree of

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ABSTRACT

Researchers face the challenge of efficiently navigating vast scientific literature while valuing printed papers in the digital age. Printed materials facilitate deeper engagement and comprehension, leading to superior exam performance and enhanced retention. However, existing digital tools often need to pay more attention to the needs of researchers who value the tactile benefits of printed documents. In response to this gap, we introduce AR-PaperSync, a transformative solution that leverages Augmented Reality (AR) and cross-device interaction technology. AR-PaperSync seamlessly integrates the physical experience of printed papers with the interactive capabilities of digital tools. Researchers can effortlessly navigate inline citations, manage saved references, and synchronize reading notes across mobile, desktop, and printed paper formats. Our user-centric approach, informed by in-depth interviews with six researchers, ensures that AR-PaperSync is tailored to its target users' needs. A comprehensive user study involving 28 participants evaluated AR-PaperSync's significantly enhanced efficiency, accuracy, and system usability and reduced cognitive load in academic reading tasks compared to conventional methods. These findings suggest that AR-PaperSync enhances the reading experience of printed scientific papers and provides a seamless integration of physical and digital reading environments for researchers.

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1. INTRODUCTION

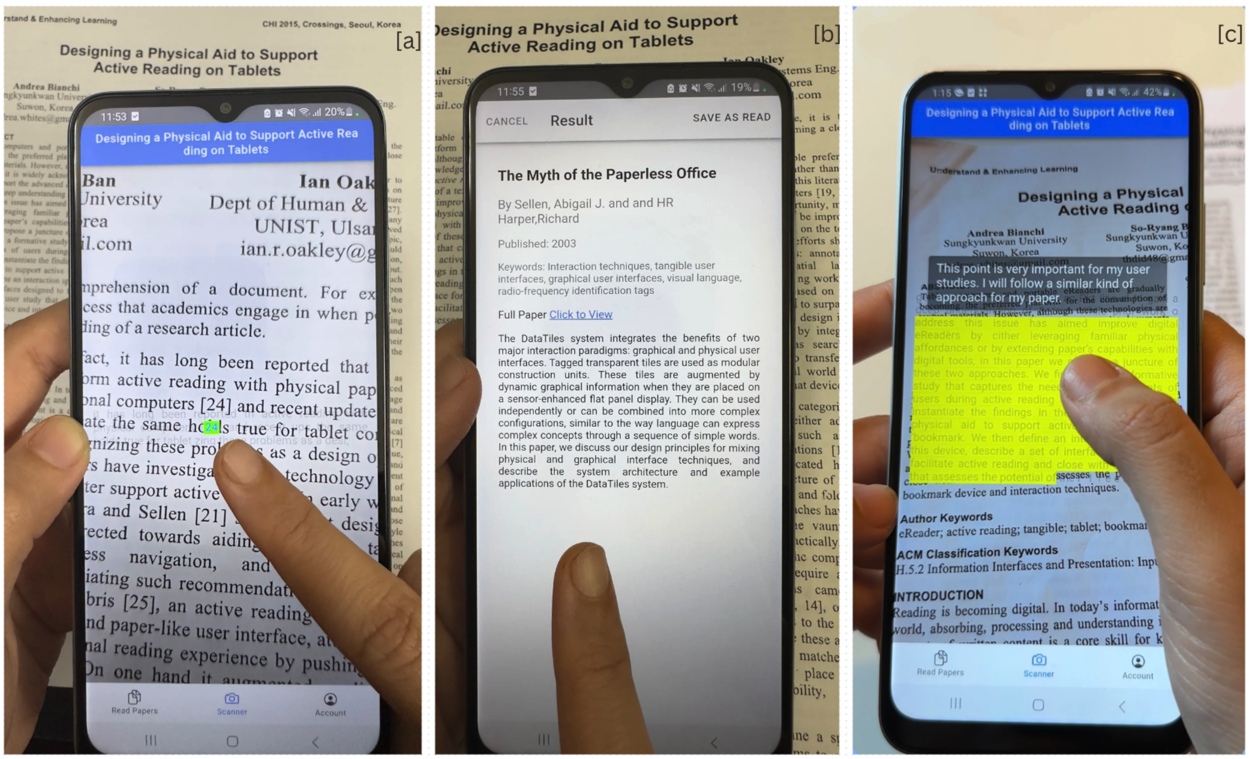


Figure 1.1. Overview of AR-PaperSync. (a) enabling users to access citations from physical documents through a mobile AR application effortlessly; (b) viewing full paper and tracking saved inline citations on physical paper; (c) enabling real-time synchronization across mobile, desktop, and printed paper formats, ensuring continuity in their research activities.

A vast expanse of scientific literature increasingly dominates the landscape of academic research. This growth necessitates an efficient modality for researchers to assimilate scholarly content. Traditionally, the academic community has shown a strong inclination towards printed scientific papers, attributed to their tangible nature facilitating deeper engagement and comprehension [17, 16]. This preference is substantiated by empirical studies indicating superior exam performance, enhanced retention, and active reading engagement when using printed materials compared to digital formats [35, 17, 16]. However, the advent of digitalization in academic research presents a dichotomy—the tactile benefits of print media versus the dynamic and interactive capabilities of digital tools [16]. Researchers often face the daunting task of manually tracking and cross-referencing inline citations on printed papers. This process can be time-consuming and disruptive to the natural flow of reading and comprehension. Also, managing saved citations in printed formats requires a lot of work. Traditional methods usually involve manual cataloguing and organization and need more efficiency and flexibility than digital tools offer [8, 19]. Such techniques are often labour-intensive and can lead to fragmented research processes, hindering the researcher's productivity and effectiveness.

Despite advancements in digital reading technologies, there remains a significant gap in solutions that effectively integrate the deep engagement and comprehension of printed papers with the convenience and interactivity of digital tools. Current research systems, while adept at enhancing digital reading experiences with tools like LiquidText [38], which provides a multitouch environment to support active reading, QuickRef [29], and CiteSee [8], designed to navigate referenced papers and review literature on desktop, and the work of Head et al. [12, 13] introduced tooltips with novel design patterns for mathematical notation and definitions, need to address the challenges faced by researchers relying on printed materials. These challenges include efficiently navigating inline citations and managing saved citations on printed papers. Another significant challenge that arises is the synchronization of reading notes and insights across mobile, desktop, and printed paper formats [32]. Previous AR systems have primarily focused on presenting paragraphs, scientific data, and images [7], as seen in applications like My Vision-AIR [2] and GeoAR [20], which introduced augmented interactive reality (AIR) tools for teaching geometry topics, animations, and multimedia to enrich adult or child reading experiences with traditional books. Similarly, CoScribe [36] integrated pen-based annotations on physical documents with digital versions, and Rzayev et al. [34] studied the impact of text placements and presentations in a VR environment. While these applications have significantly advanced text presentation, enhanced the AR reading experience for adult learners, facilitated image visualization, combined tangible and digital media with pens, and improved the teaching of geometric shapes, there is still a need for a solution that specifically addresses the challenges researchers face while reading printed papers. This solution should facilitate the navigation of inline citations and seamlessly update reading notes between physical and digital environments. Researchers are often required to maintain separate systems for note-taking and reference management for their printed and digital papers, leading to disjointed workflows, increased cognitive load, and a higher likelihood of critical insights being overlooked or lost in the transition between formats.

Our motivation stems from the need to cater to researchers who prefer printed papers while recognizing the benefits of digital enhancements. We focus on developing a solution that respects and enhances traditional reading practices, bridging the gap between the physical and digital realms. To address researchers' challenges while reading printed papers, we introduce AR-PaperSync, an innovative solution for mobile and desktop that leverages Augmented Reality (AR) and cross-device interaction technology (Figure 1.1). AR-PaperSync represents a pivotal step towards revolutionizing how researchers interact with scholarly content. By seamlessly integrating digital enhancements into the physical realm of printed papers, the AR-PaperSync mobile application offers a transformative reading experience that caters to traditionalists' preferences while harnessing modern technology's capabilities.

At the core of AR-PaperSync lies a commitment to enhancing the reading journey for researchers who treasure the tangible qualities of printed papers. In response to the challenges faced by researchers relying on printed materials, AR-PaperSync offers solutions that make the reading experience seamless and efficient. Inline citations, which can be frustrating and disruptive to the natural flow of reading and comprehension, become effortless to navigate with AR-PaperSync. Through AR overlays, researchers can instantly access additional information about citations, view related references, and explore cited works in a fluid and non-disruptive manner. Saved citations, a labor-intensive aspect of managing printed papers, are seamlessly organized and managed within the AR-PaperSync ecosystem. The system intelligently recognizes and catalogues saved references, enabling researchers to access detailed bibliographic information with a simple gesture. Furthermore, AR-PaperSync addresses the challenge of reading note synchronization by providing a unified platform for researchers to create, manage, and sync their notes across mobile, desktop, and printed paper formats. This synchronization enhances the researcher's productivity and ensures that valuable insights and annotations are preserved, irrespective of the format.

Our development of AR-PaperSync is guided by a user-centric approach, informed by in-depth interviews conducted with 6 volunteers representing diverse academic backgrounds. This interview ensures the tool is meticulously tailored to its target users' needs and operational processes. Subsequently, we conducted a comprehensive user study involving 28 participants to assess

AR-PaperSync's practical utility in real-world scenarios. The evaluation encompassed the tool's effectiveness in facilitating seamless navigation of inline citations, efficient management of saved references, and the seamless sharing of reading notes across various formats. The outcomes of the study indicate that AR-PaperSync significantly improves the efficiency and accuracy of navigating citations and synchronizing notes across mobile, desktop, and printed paper formats. Analysis of usability questionnaires, including the System Usability Scale (SUS) and the NASA Task Load Index (NASA-TLX)), underscores AR-PaperSync's remarkable capacity to reduce cognitive burdens and ease of integration into researchers' workflows.

In explicit terms, this paper presents the following key contributions:

- Introduce an innovative scientific paper inline citation searching tool—AR-PaperSync—that overcomes existing limitations by seamlessly integrating physical and digital versions of scientific papers using Augmented Reality (AR) and cross-device interaction. Unlike prior approaches focusing on either reading articles [6, 19, 12, 13] or navigating citations [29, 8] on digital platforms, AR-PaperSync harmonizes the two, enabling users to access citations from physical papers through a mobile application effortlessly.

- AR-PaperSync enables real-time synchronization across mobile, desktop, and printed paper formats, ensuring continuity in their research activities. By facilitating syncing reading notes from digital to physical paper and tracking saved inline citations on physical paper, AR-PaperSync provides a smooth and consistent user reading experience.

- Insights gathered from interviews with (N=6) researchers formed the basis for AR-PaperSync's user-centric design to ensure the tool is meticulously tailored to its target users' needs and operational processes.

- Validation of AR-PaperSync's effectiveness through a user study involving (N=28) participants demonstrated its proficiency in efficiently navigating and tracking inline citations from printed papers and seamlessly connecting various reading environments to share reading notes.

In the upcoming chapters, we will delve deeper into our research. Chapter 2 comprehensively reviews related work, while chapter 3 discusses the interviews conducted. Chapter 4 delves into the design and architecture of AR-PaperSync, and chapter 5 presents the user study conducted.

Chapter 6 focuses on the results obtained from our research, and in chapter 7, we engage in a detailed discussion of these findings. Finally, chapter 8 concludes our work and outlines future directions for this research.

2. RELATED WORK

Previous research has focused on improving the digital reading experience of scholarly content. Several systems have been developed for digital readers to navigate referenced scientific documents [29, 31, 37], exploring relevant prior work [8, 30, 18], linking sentences with table cells to enhance interactivity [19], and showing definitions of technical terms and symbols [12]. Additionally, AR technologies have been employed to create immersive reading experiences [34], including presenting paragraphs, scientific data and visual content [2, 7, 9, 5, 3]. However, existing works still need a specific focus on seamlessly integrating physical and digital versions of scientific papers, a critical aspect our proposed tool, AR-PaperSync, aims to address.

2.1. Systems for Reading in Digital Space

Numerous systems have been developed to enhance the reading experience of scientific papers in digital formats [1, 37, 38]. These systems often improve text readability, provide contextual information, explore prior work and content navigation. For instance, Park et al. [29] developed QuickRef, an interactive reader, to assist scholars in navigating referenced documents that provide additional information about cited papers. It addresses the challenges of navigating cited papers by presenting meta-information, an overview, and relevant information. Additionally, Chang et al. [8] introduced a personalized literature review tool, CiteSee, to enhance the reading experience of scientific papers. It leverages a user's previous research activities to provide contextual information and facilitate exploring relevant prior work. Kim et al. [19] conducted a user study comparing their interactive document reader, which links sentences to table cells, with a baseline reader. This study highlights the potential of interactive document readers to reduce split attention and improve document reading. Additionally, Head et al. [12, 13] introduced an augmented reading interface, pioneering innovations like tooltips for position-sensitive definitions, decluttering filters, and novel visual design patterns for mathematical notation, aiming to improve the readability and comprehensibility of research papers in digital formats. However, it is worth noting that while these endeavours have predominantly focused on enhancing the digital reading experience, there is evidence suggesting a preference for printed articles over e-books among readers [35]. In light of this, our research takes a different approach by prioritizing enhancing the reading experience for printed paper readers. We achieve this by developing a smartphone-based AR system that supports navigation and facilitates tracking of inline citations while providing digital reading notes on printed documents, offering a novel solution for improving the traditional reading experience.

2.2. Reading Scientific Papers using Augmented Reality

Augmented reality (AR) has transformed many areas of research and education. Some AR systems are designed to visualize scientific data, simulations, images, and user interfaces [20, 2, 34, 28, 39]. Rzayev et al. [34] studied how different text presentations (like RSVP and paragraph) and text placements (world-fixed, edge-fixed, head-fixed) impact the VR environment. Meanwhile, Al-Ali et al. [2] introduced an augmented interactive reality (AIR) tool named "My Vision-AIR." It's designed to enrich adult reading experiences by infusing AR into traditional books. This app uses 2D/3D graphics, animations, virtual buttons, translations, and multimedia to make reading more engaging and immersive. On another note, Bianchi et al. [6] launched eTab, a tool to elevate the tablet reading experience. Kirner et al. [20] contributed to the AR landscape by developing the interactive book GeoAR, leveraging Augmented Reality for teaching Geometry topics. Meanwhile, Rajaram et al. [33] introduced Paper-Trail, a transformative tool designed to enrich paper-based learning with digital media, animations, and clipping masks. These AR applications have significantly advanced text presentation, enhanced the reading experience for adult learners, facilitated image visualization, and improved the teaching of geometric shapes. However, our research focuses on a unique aspect within the AR domain, addressing the needs of researchers by facilitating the navigation of inline citations, tracking saved references in printed papers, and seamlessly updating reading notes between physical and digital environments. Our work bridges the gap between traditional and digital reading experiences by ensuring a consistent reading journey, offering valuable contributions to the field.

2.3. Integrating Scientific Papers with Digital Environments

As technology evolves, a growing interest has been syncing traditional paper documents with digital environments. Efforts have been made to bridge the gap between traditional printed content with digital enhancements—mobile, desktop—facilitating real-time synchronization and interaction across platforms [14, 4, 15, 11]. Among these, Qian et al. [32] developed an AR-based system to enhance interactions with printed documents through layout recognition, leading to more accurate and efficient annotations. Steimle et al. [36] created CoScribe, which integrates pen-based annotations on physical documents with digital versions. Similarly, Guimbretière [10] introduced PADD (Paper Augmented Digital Documents), blending paper and digital interactions via patterns recognized by a digital pen. Motoki and Koike [21] also contributed with "EnhancedDesk," a desktop interface merging paper with digital information through 2D matrix codes. These developments highlight the potential of combining tangible and digital media using various tools like pens, tabletops, or projectors. Building on this foundation, we have developed AR-PaperSync, an AR mobile application designed to enhance the reading experience, especially for scholars accustomed to traditional scientific papers. This innovative app reduces the need for additional devices and uses AR to connect printed documents with their digital counterparts fluidly. It simplifies access to inline citations, tracks saved references on physical papers, and updates reading notes across mobile, desktop, and printed formats through AR and cross-device interaction.

3. INTERVIEW

In the initial phase of the AR-PaperSync project, we conducted interviews to gain insights into how researchers interact with inline citations and reading notes during their academic reading and to identify common limitations. Understanding these aspects was crucial for developing targeted design goals for AR-PaperSync. We recruited 6 participants with diverse educational backgrounds, including 3 PhD candidates, 2 Master's, and 1 Bachelor's student from transportation and logistics, microbiology, computer science, biochemistry, and mechanical engineering. The interviews, lasting approximately 20 minutes each, followed a semi-structured format. We focused on three main questions to uncover participants' reading preferences and practices, using additional devices with printed papers and tools for managing citations and notes while reading printed papers, with follow-up questions to clarify their responses.

3.1. Reading Preferences and Practices

The participants' responses revealed various reading preferences, emphasizing the varied reliance on printed and digital papers. One participant highlighted a strong preference for the *"tangibility of printed papers"* for in-depth research, often engaging with *"3-6 papers per week"*. This preference for physical copies was echoed by another who *"prefers printed papers for initial reading"* and consistently reads *"3-4 papers weekly in printed form"*. In contrast, some participants balanced their use of digital and printed formats, with one noting the practice of printing *"complex papers for better comprehension"* while generally favoring digital formats for convenience. Another described printing papers primarily for *"group discussions"*, indicating a situational reliance on physical documents. These insights underscore the diverse academic reading habits, ranging from a predominant preference for printed materials for detailed study to a strategic combination of digital and physical mediums.

3.2. Using Additional Devices with Printed Papers

The participants' approaches to using additional devices with printed papers varied significantly, reflecting a broad spectrum of practices in academic research. Several participants described using a laptop as a complementary tool for their reading process. One participant specifically mentioned using a laptop for *"cross-referencing information and deeper analysis"*, highlighting the role of digital tools in enhancing the understanding of printed materials. Another researcher noted the use of a laptop for *"searching and saving relevant citations on printed paper"*, illustrating how digital tools facilitate the management of academic resources. In contrast, one participant pointed out that they *"rarely use a laptop in conjunction with printed papers"*, suggesting a preference for more traditional, paper-centric approaches. Interestingly, a dual-screen setup was mentioned for working on multiple tasks simultaneously, indicating that researchers use one screen to display the digital version of the printed paper they are reading and a second screen for referencing online resources or viewing supplementary materials. A tablet was also noted for additional research, particularly when not at a desk, indicating a preference for more portable digital solutions. These varied responses underscore how researchers combine digital and physical resources to enhance these multifaceted reading and research habits. They also conclude it consumes time to integrate technology with printed papers during their research activities.

3.3. Tools for Managing Citations and Notes

The methods employed by participants for managing citations and notes while reading printed papers demonstrated a diverse range of practices. Several participants described manual strategies, such as checking inline citations by hand and using sticky notes for marking influential citations and thoughts. This traditional approach, while familiar, was often cited as time-consuming and sometimes led to challenges like misplacing physical papers. One participant specifically mentioned the frustration of losing papers, highlighting the limitations of purely manual systems. Others integrated digital tools into their workflow: one researcher used a digital tool for managing citations coupled with handwritten notes on paper margins, while another used a mobile app for scanning and organizing citations, occasionally complementing this with digital notes. A mix of digital and manual methods was standard, with one participant typically using a desktop for note-taking at home but switching to manual checks and paper markings while on campus. These varied practices underline the need for a system that seamlessly integrates and enhances these methods, providing a more efficient and organized way to manage citations and notes.

3.4. Design Goals

The insights gleaned from the interviews with participants have directly informed the development of specific design goals for AR-PaperSync. These goals address the challenges and preferences in managing inline citations and notes and integrating digital tools with printed papers. The following design goals aim to enhance the academic reading experience by leveraging augmented reality (AR) and digital synchronization technologies:

- **[DG1]** Help researchers find inline citations from printed scientific papers connecting digital AR view using AR mobile applications. This goal aims to enhance the traditional method of accessing citations, improving overall reading efficiency, particularly for those who prefer printed materials.

- **[DG2]** Save inline citations, offering a seamless way to manage and organize these references effectively.

- **[DG3]** Enables real-time synchronization of reading notes across printed paper, mobile, and desktop applications. This goal addresses the diverse use of technology and the challenges in managing citations and notes, aiming for a cohesive research process that integrates the physical and digital papers.

4. AR-PAPERSYNC SYSTEM

The development of AR-PaperSync represents a pioneering endeavor at the intersection of mobile augmented reality, digital document management, and real-time synchronization technologies. Here, we delve into the intricate architectural design and meticulous implementation that underpins the AR-PaperSync system, showcasing how it transforms the traditional reading experience into a dynamic and interactive journey.

4.1. Architectural Overview

The AR-PaperSync system is architecturally divided into three main components: the mobile application for AR-based reading, the desktop application for taking digital notes associated with the printed paper, and the back-end cloud service. Each component is meticulously designed to interact synergistically, providing a robust and user-centric experience. Figure 4.1 illustrates the architectural overview of AR-PaperSync.

4.1.1. Mobile AR Application

The mobile AR application is meticulously developed using the Ionic 7 framework, Angular 16 for handling the application logic, and TypeScript 5 for scripting requirements. Capacitor 5 is a cross-platform bridge, enabling seamless access to native device features. The client service within the mobile AR application communicates over HTTP with the cloud service, utilizing JSON strings for efficient data exchange related to paper titles, inline citations, user-saved citations, and reading notes. Figure 4.2 encapsulates the core functionalities of the mobile AR, highlighting features such as the AR camera, paper title detection, inline citation display, and options to mark as read or access the entire paper.

Camera and AR Module. The mobile application leverages the device's camera and integrates augmented reality functionalities to detect and interact with physical papers effectively. This module initiates the document recognition process, captures images optimized for OCR processing, and overlays interactive AR elements on the physical paper. To achieve this, we utilized the capacitor camera preview to develop a customized camera interface compatible with Android and iOS platforms, incorporating AR views. Additionally, the ImageCompressService is implemented to

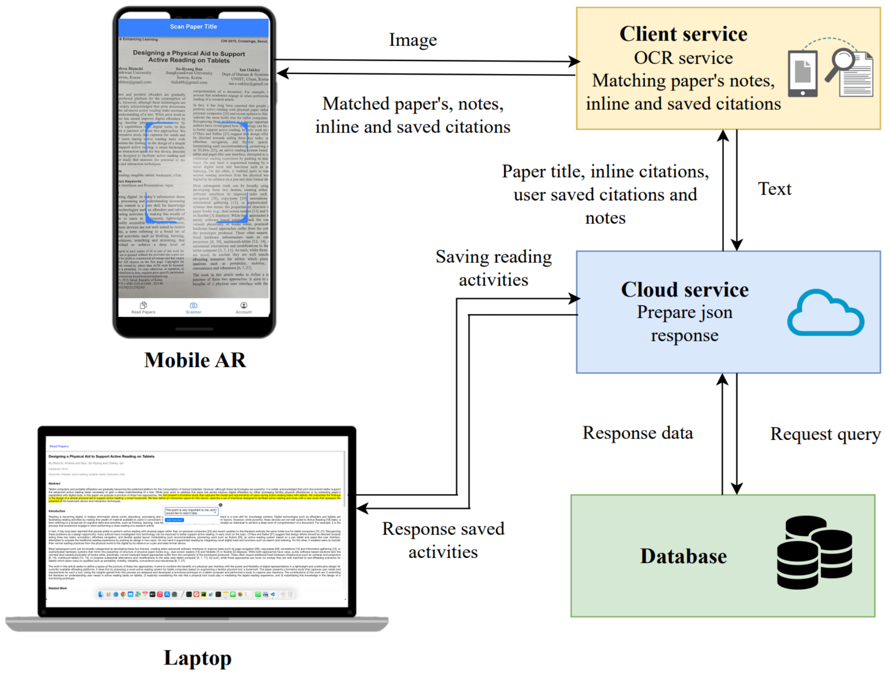
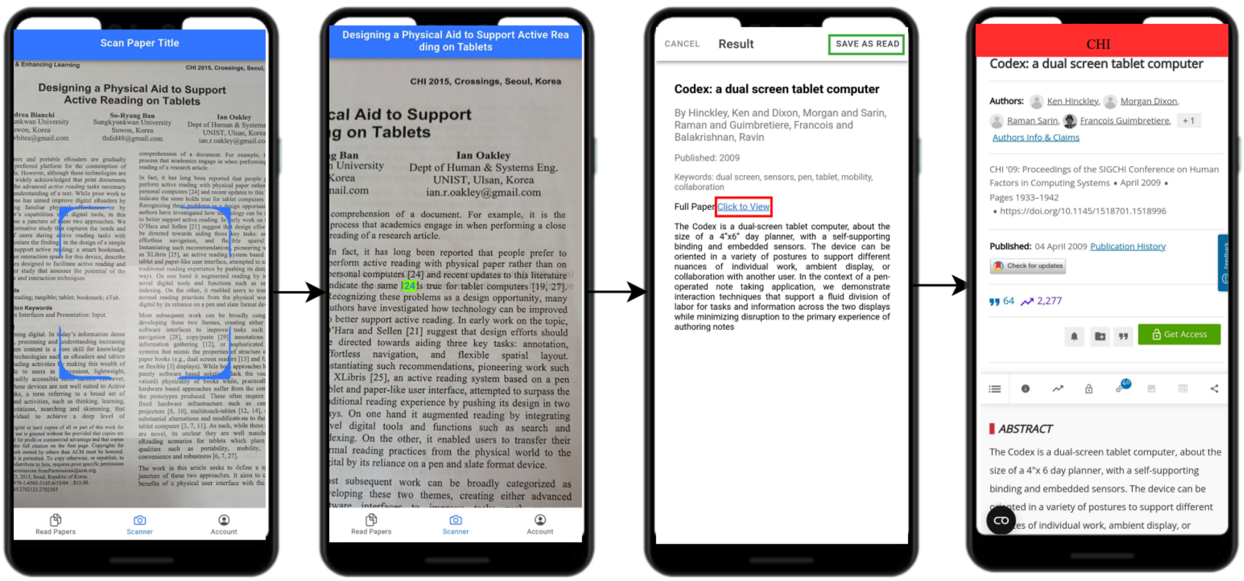


Figure 4.1. Architectural Overview. AR-PaperSync uses cloud and client service to facilitate the synchronization of matched paper titles, inline citations, reading notes, and saved citations across mobile applications (Mobile AR). Users utilize desktop applications (Laptops) to create and store reading notes, with these notes being stored in the cloud database and synchronized in real time for mobile AR access.

compress captured images to a maximum of one megabyte, enhancing processing efficiency without compromising quality.

OCR Integration. Upon capturing the optimized image, the OCR module facilitates extracting and processing text content from the document, encompassing titles, inline citations, and reading notes. Given the criticality of accuracy and processing speed, a robust algorithm is imperative to effectively accommodate diverse fonts, sizes, and document conditions. To address this, we integrated Tesseract 4, leveraging its new neural net (LSTM) based OCR engine to extract text from images with unparalleled precision and efficiency.

User Interaction Layer. The user interaction layer is pivotal in rendering interactive elements on the user's device, facilitating a compelling AR experience. Users can tap on augmented citations to access detailed information, navigate to cited papers seamlessly, or bookmark them for future reference. Moreover, this layer enables users to visualize reading comments associated with printed papers, enhancing their comprehension and engagement. Selected texts on printed papers are



(a) (b) (c) (d)

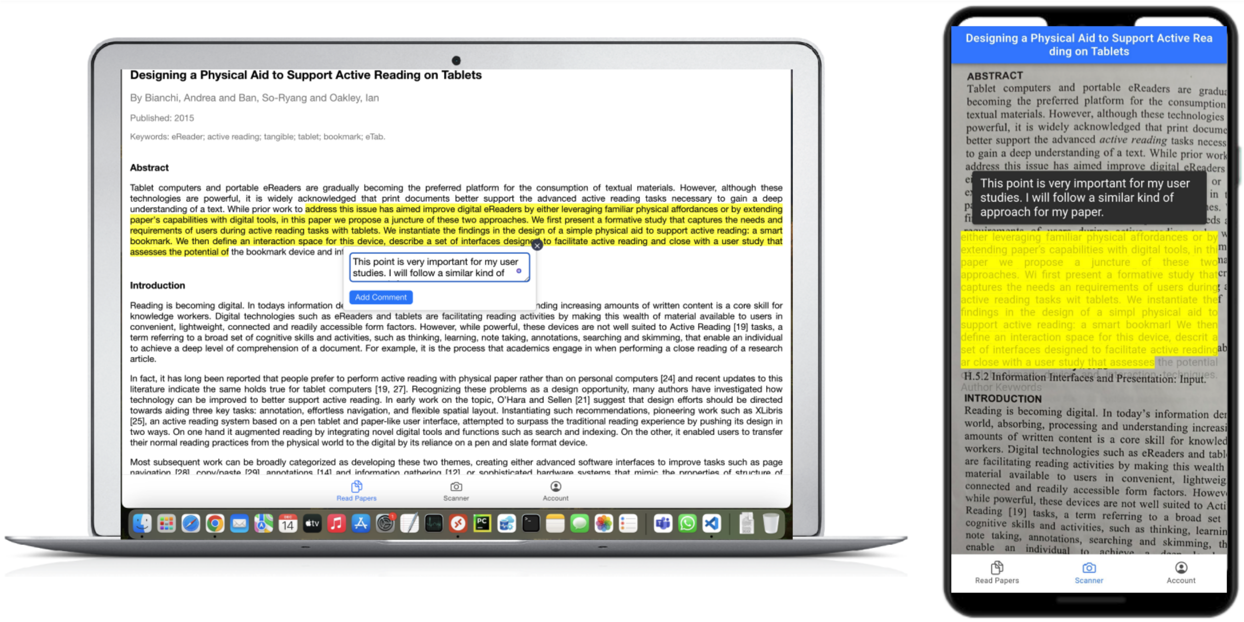
Figure 4.2. Mobile AR. (a) camera and AR module poised for text processing; (b) detection of paper title accompanied by inline citation, visualized within the AR view; (c) upon selecting augmented citations, detailed information becomes accessible, accompanied by options to mark as read or view the entire paper; (d) display of the complete paper sourced from the published site.

highlighted through the AR camera, and associated comments become accessible upon clicking the highlighted text within the AR view, fostering an immersive and interactive reading environment.

4.1.2. Desktop Application

The desktop application is an interactive platform that enables users to engage with digital renditions of academic papers while offering robust features for reading, annotating, and organizing documents. Developed utilizing Angular 16 and TypeScript 5, the desktop application ensures a responsive and user-centric interface, facilitating seamless navigation and interaction. Figure 4.3 delineates the main components of the digital reading interface, emphasizing note-taking functionalities and synchronization capabilities with mobile AR.

Digital Reading Interface. The Digital Reading Interface is designed to present digital documents efficiently, accommodating various PDF formats while prioritizing an intuitive user experience. Leveraging libraries such as PDF.js enhances the presentation of PDF documents, ensuring clarity and accessibility. Users are empowered to annotate texts, add or modify reading notes, and organize content, thereby facilitating efficient academic engagement.



(a) (b)

Figure 4.3. Desktop Application Integrated with Mobile AR. (a) digital reading interface showcasing scientific papers with annotated notes, allowing users to add or modify annotations; (b) mobile AR application enabling real-time access and interaction with annotations on printed papers, utilizing the AR camera's capabilities.

Note Synchronization with Mobile AR. The desktop application facilitates a bidirectional data exchange with the Cloud Service Backend, ensuring synchronized interactions across digital and physical platforms. Notes, highlights, and annotations created within the desktop application are seamlessly integrated with the mobile AR application, enabling real-time updates and reflections. The desktop application communicates with the cloud service via HTTP, optimizing data exchange through JSON strings to synchronize users' reading notes efficiently. Consequently, users engaging with the mobile AR application can access and interact with notes on printed papers in real time, leveraging the capabilities of the AR camera.

4.1.3. Back-end Cloud Service

The Cloud Service Backend is a crucial element within the AR-PaperSync system, functioning as a centralized repository and a processing hub for user data, document information, and synchronization directives.

Database and Storage. Utilizing MS SQL Server, the backend efficiently manages a vast dataset encompassing user profiles, document metadata, annotations, and citations. The database design focuses on scalability, query efficiency, and data integrity. Specifically, we maintain essential paper details with associated citations in a structured manner. A dedicated citation table also establishes one-to-many relationships, ensuring comprehensive data organization. User-generated reading notes are systematically stored in a notes table, associating each entry with specific user and paper identifiers.

API and Data Services. The backend facilitates seamless interactions through RESTful APIs, leveraging Node.js to facilitate data exchanges between mobile and desktop clients. These services proficiently manage tasks such as storing citations, retrieving detailed paper and citation information, and synchronizing reading activities across platforms. Prioritizing user privacy and security, the backend incorporates robust measures, including authentication protocols and data encryption, safeguarding sensitive user information.

4.2. System Features

In realizing the objectives set forth for AR-PaperSync, we've successfully implemented three pivotal features: the exploration of inline citations, the saving of inline citations within the AR environment, and the presentation of reading notes on physical papers via augmented reality.

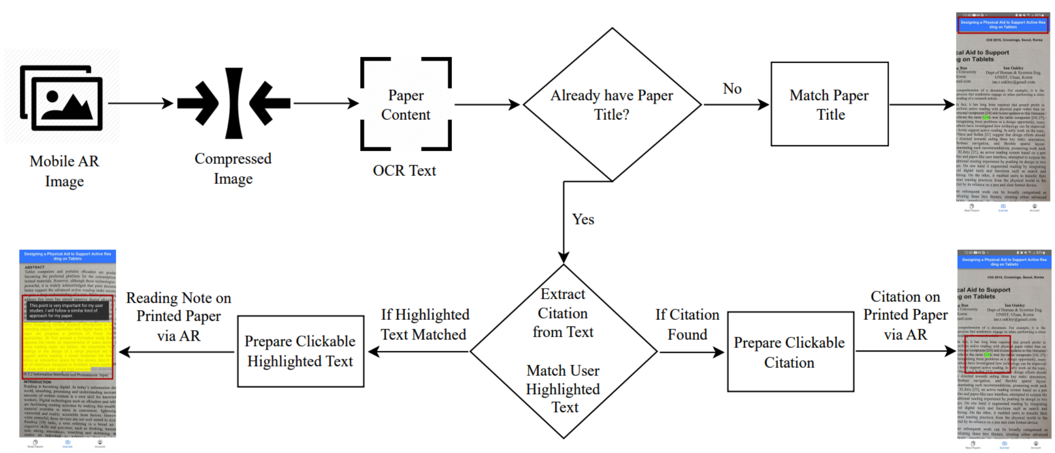


Figure 4.4. Detailing the exact sequence of image processing steps and their seamless integration into the AR mobile view, the system adeptly presents paper titles, inline citations, and reading notes.

4.2.1. [DG1] Explore Inline Citations using AR

Our primary design goal is to empower users to explore inline citations while reading printed papers. To retrieve citation details, readers simply scan the paper title using the AR camera view, obtaining real-time information. This establishes the foundation for acquiring citations from a specific paper. By scanning the content through the camera, users seamlessly access digital citations overlaid on the printed paper through our mobile AR application. Clicking on citations reveals detailed paper information, enhancing the reading experience with immediate access to supplementary materials and contextual insights. Figure 4.2 illustrates the step-by-step process of obtaining the paper title and its citations.

To optimize the citation exploration performance, real-time image compression occurs before sending the image to the OCR engine. The OCR service then converts the compressed image into plain text. If the application lacks a predefined paper title, it initiates a matching process with the paper storage. Upon successfully identifying the paper title, the application proceeds to search for citations within the text. The system is adept at extracting citations formatted in two prevalent styles: numerical references within square brackets, e.g., [number] or [number 1, number 2] [25, 24, 23], and author-year citations in parentheses, e.g., (Author et al., year) or (Sample and Example, year) [27, 35]. These extracted citations are then presented as clickable buttons on the AR view, accurately positioned based on the layout of printed paper citations. Readers can effortlessly click on these digital citations to access and explore detailed paper information. Figure 4.4 provides a visual representation of the workflow, illustrating how images are processed and seamlessly integrated into the AR mobile view.

4.2.2. [DG2] Save Inline Citations on AR View

Building upon the foundation laid by exploring inline citations using AR, the AR-PaperSync system seamlessly integrates a feature allowing users to save identified inline citations for future reference. Upon successfully obtaining citation details through the AR camera view, users are presented with an intuitive "Save as Read" button. Clicking on this button initiates the citation storage in the user's reading activity database, enabling them to revisit and explore saved citations at their convenience.

The saved inline citations are stored securely within the cloud service backend, ensuring accessibility from any device and platform. As users continue scanning for inline citations, the AR view intelligently distinguishes between citations saved as read and those yet to be explored. Already saved citations are visually differentiated with a distinct background color, giving users a quick visual cue indicating their "as-read" status. This design enhances the user experience by efficiently tracking and managing saved citations, promoting a seamless transition between exploring new citations and revisiting previously saved content. Figures 4.2 b and c visually outline the process, illustrating how users can save inline citations and subsequently identify their saved status while exploring printed papers using the AR view.

4.2.3. [DG3] Real-time Synchronization of Reading Notes

A cornerstone of AR-PaperSync's functionality is the seamless synchronization of users' reading notes, fostering a cohesive research experience across mobile, desktop, and printed paper formats. The system ensures real-time continuity, allowing users to take notes using the desktop application, with these notes dynamically synchronized across all platforms.

In the desktop application, users can meticulously annotate digital documents, highlighting essential sections and adding insightful comments to enhance their understanding. These reading notes are stored in the cloud service's dedicated notes table, associating each note with the user, paper, and selected text. This robust backend infrastructure enables secure storage and efficient retrieval of users' reading notes.

The real-time synchronization extends to the mobile AR environment, where users can witness their reading notes seamlessly appearing on printed papers in real time. Leveraging advanced OCR capabilities, the system extracts text from the printed paper, matching it with the highlighted text from the desktop application. When a match is found, the system dynamically prepares clickable highlighted text on the AR view, precisely overlaying the selected text on the physical document. Users can effortlessly click on these highlighted sections to reveal the associated comments from their desktop application.

This innovative approach ensures that users' interactions with academic content, whether on a desktop application or printed paper, remain synchronized and accessible in real time. Figure 4.4 illustrates the workflow of image processing to AR mobile view, and Figure 4.3 showcases how reading notes created on the desktop application seamlessly translate into highlighted sections on printed papers via the AR view, providing users with an integrated and fluid research experience.

5. USER STUDY

We present a comprehensive user study of AR-PaperSync, a system that innovatively combines augmented reality (AR) with traditional paper-based reading of scientific documents. This study is designed to critically assess the impact of AR-PaperSync on enhancing the academic reading experience, emphasizing its usability.

5.1. Research Hypotheses

Through a formal face-to-face usability study, we seek to answer the following pivotal research questions using the Goal Question Metric (GQM) [22] framework to define the goals of our study. This section outlines the research goals and corresponding hypotheses to guide our assessment of AR-PaperSync in enhancing the academic reading experience.

Goal 1: Assess how AR-PaperSync influences users' efficiency and accuracy in accessing information compared to conventional methods.

Hypothesis 1: There is a significant improvement in efficiency and accuracy when using AR-PaperSync compared to conventional methods for accessing information in scientific printed papers.

Goal 2: Investigate the impact of AR-PaperSync on system usability and cognitive load during academic reading activities.

Hypothesis 2: AR-PaperSync reduces cognitive load and enhances the system usability of academic reading activities compared to traditional methods.

Goal 3: Examine the usefulness of AR-PaperSync features in enhancing the reading experience of printed scientific papers.

Hypothesis 3: AR-PaperSync's features significantly improve the reading experience of printed scientific papers compared to reading without AR-PaperSync.

5.2. Participants

The study involved 28 participants, 17 males, and 11 females, with an average age of 26 $\pm$ 4 years. The participant group comprised 15 PhD and 13 master's students from the university. Among the participants, 18 reported regularly reading physical and digital scientific papers. In contrast, 3 participants primarily used printed materials, and 7 preferred exclusively with digital papers. None of the participants had prior experience reading papers using an AR reading tool. This study was conducted as human subjects research and received approval from the Institutional Review Board (IRB). Each study session was conducted face-to-face, lasting between 20 and 30 minutes, and took place in the Department of Computer Science.

5.3. Experimental Design

In our study, twenty-eight participants were randomly divided into two groups to assess the effectiveness of AR-PaperSync compared to traditional reading methods. Group 1 utilized AR-PaperSync, and Group 2, employing the Baseline method, relied on traditional printed scientific papers and standard digital devices like computers or mobiles. Both groups were tasked with three specific activities during their reading sessions: finding inline citations, saving important citations, and taking reading notes. The experiment was conducted in a controlled environment using standardized equipment, including a MacBook Pro 15 inches, an Android phone equipped with the AR-PaperSync app, and a carefully selected short paper from the CHI EA archives, chosen for its readability and suitability for the participant's academic levels.

5.4. Procedure

The experimental procedure was meticulously planned to ensure a fair and effective comparison between AR-PaperSync and the conventional Baseline method. The study commenced with participants providing formal consent, followed by a pre-study questionnaire to gather baseline data on their experiences and expectations. Subsequently, participants underwent a focused training session tailored to each method to ensure familiarity with the respective technologies and techniques. The core of the study involved participants engaging in a series of reading tasks designed to replicate real-world academic reading scenarios. Upon completing these tasks, a post-study questionnaire was administered to collect data on participants' usability, cognitive load experienced during the tasks, and effectiveness of the methods explored. In essence, the experimental sequence was as follows:

Step 1: Initial Setup. Upon arrival, all participants were first briefed about the study's purpose and technologies. Following this, they provided their formal consent to participate.

Step 2: Pre-Study Survey. Participants then completed a pre-study survey to assess their prior knowledge and experience with mobile augmented reality (AR) technologies and their habits concerning reading scientific papers. This step ensured a baseline understanding of each participant's starting point.

Step 3: Training Session. After the pre-study survey, Group 1 participants received comprehensive training on utilizing AR-PaperSync, focusing on how to use its AR features effectively on mobile devices. Conversely, Group 2 participants were instructed on the Baseline method of reading from printed papers, supplemented with digital tools like computers or mobile devices for additional support.

Step 4: Engagement in Reading Tasks. In this step, participants were instructed to read the provided CHI EA printed paper comfortably. Then, they engaged in the reading tasks, which involved finding inline citations, saving necessary citations, and taking reading notes on the paper. Each participant completed each reading task at least 3 times. To ensure a thorough evaluation of the technology's usability and effectiveness, each participant completed each reading task at least three times. These tasks mirror typical academic reading scenarios, ensuring participant interactions were as natural and authentic as possible. For finding inline citations, Group 1 used the AR-PaperSync app to locate and read referenced papers, while Group 2 searched for referenced paper titles on the internet. To save necessary citations, Group 1 could save and view them in AR via the AR-PaperSync app, whereas Group 2 marked them on printed paper or saved them on their computer. For taking reading notes, Group 1 utilized the AR-PaperSync desktop tool for note-taking and the mobile app for viewing notes alongside the printed paper. Group 2 participants took notes directly on the printed paper or a computer.

Step 5: Post-Study Questionnaire and Feedback. Upon completing the reading tasks, participants were asked to complete the System Usability Scale (SUS) and NASA Task Load Index (NASA-TLX) questionnaires to evaluate their experiences regarding system usability and cognitive load. Participants who used AR-PaperSync also provided qualitative feedback focusing on their perceptions, usability experiences, and potential improvements for the system. This feedback was gathered through the following interview questions:

1. How are the AR-PaperSync features useful to support the reading experience on printed paper?
2. Are there any AR-PaperSync features you will use in the future if the application is available?
3. Is there anything you want to improve or add to the AR-PaperSync?

5.5. Data Collection

Our study's data collection and analysis process was meticulously designed to be comprehensive and systematic, capturing both quantitative and qualitative aspects of user interactions with AR-PaperSync and the Baseline method.

Quantitative Data Collection. In the quantitative phase of our study, meticulous attention was given to recording each participant's time to complete specific tasks. These tasks included finding inline citations, saving necessary citations, and taking reading notes. The completion time for each task was calculated by dividing the total time taken to complete the task by the number of attempts. For example, if a participant attempted to find three inline citations and the total time taken was 27 seconds, the completion time for this task would be 9 seconds. To ensure fair comparisons, each participant completed each task using AR-PaperSync or Baseline at least three times, and we calculated the average time in seconds for each task. Additionally, we assessed the accuracy with which these tasks were executed, particularly in correctly identifying citations and saving citations and notes. As with the same formula used to calculate average time, we considered the average accuracy for each participant. For instance, if a participant successfully found two inline citations out of three attempts, the accuracy for this task was calculated as $2/3 \times 100\%$. Upon completing these tasks, participants were asked to fill out the System Usability Scale (SUS) and the NASA Task Load Index (NASA-TLX) questionnaires. These instruments provided valuable quantitative measures of usability and cognitive load, respectively. The data collected from these sources were integral to evaluating the functional effectiveness of AR-PaperSync compared to the Baseline method.

Qualitative Data Collection. The qualitative dimension of our study concentrated on acquiring more profound insights into the user experience and perceptions of AR-PaperSync. This was accomplished through a series of interviews, where participants responded to three critical questions outlined in section 5.3. These questions were carefully crafted to probe the usability and practicality of AR-PaperSync's features. The feedback from these interviews was instrumental in understanding aspects of the user experience that extended beyond the quantitative data. In addition to these interviews, observational notes were taken during the tasks to document user behaviour, challenges faced, and overall engagement with the system.

6. RESULTS

We evaluate the AR-PaperSync system by thoroughly examining quantitative and qualitative outcomes and comparing them to a baseline. These assessments aim to empirically confirm the system's impact on the user experience during academic reading tasks.

6.1. Quantitative Evaluation

Completion Time. Our evaluation began with a thorough examination of completion time, revealing a significant reduction in task completion duration when AR-PaperSync was tested. Statistical analyses were employed to validate the system's clear superiority over the baseline. On average, participants demonstrated remarkable efficiency, completing tasks a stunning 90% faster with AR-PaperSync compared to the baseline system. Notably, the analysis uncovered substantial improvements in completion time, particularly in inline citations. While the baseline required an average of 30 seconds for this task, AR-PaperSync accomplished it in a mere 9 seconds. Similarly, the time taken for reading notes and saving citations was reduced by 70% and 40%, respectively, when AR-PaperSync was compared to the baseline. Paired-sample t-tests provided robust evidence of AR-PaperSync's efficiency, consistently demonstrating significantly reduced completion times compared to the baseline across all tasks: inline citations *(t-statistic = -6.21, $p < 0.001$)*, reading notes *(t-statistic = -5.78, $p < 0.001$)*, and saving citations *(t-statistic = -3.85, $p < 0.001$).* For a comprehensive breakdown of completion time across these three tasks, please refer to figure 6.1.

Accuracy. Accuracy in task completion was significantly improved with AR-PaperSync. We used paired-sample t-tests to establish that the system outperformed the baseline in saving inline citations and note-taking activities. With AR-PaperSync, the average accuracy for reading notes and saving citations reached 91% and 94%, respectively, representing a 10% improvement over the baseline. Notably, inline citations saw the most substantial accuracy enhancement, with AR-PaperSync achieving near-perfect performance at 97%, while the baseline lagged behind at 80%. For a detailed performance comparison between AR-PaperSync and the baseline, refer to figure 6.2. Paired-sample t-tests revealed that AR-PaperSync exhibited higher accuracy than the baseline in inline citations *(t-statistic = 4.26, $p < 0.001$)*, saving citations *(t-statistic = 2.13, $p < 0.05$)*, and reading notes *(t-statistic = 1.47, $p < 0.1$).*

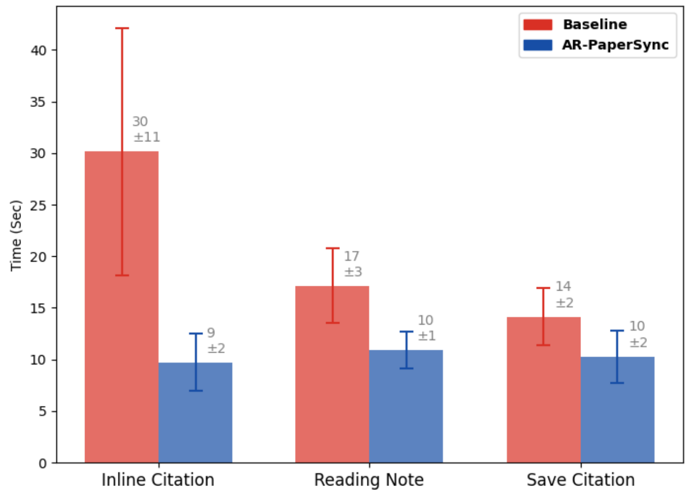


Figure 6.1. Comparative analysis of completion time across inline citations, reading notes, and saving citations with AR-PaperSync and the baseline system.

Cognitive Load. Our examination of cognitive load dimensions, assessed through NASA-TLX measures, unveiled compelling outcomes. AR-PaperSync consistently showcased its remarkable capacity to reduce mental workload across various dimensions significantly. Participants experienced substantial alleviation in mental, physical, and temporal demands, accompanied by heightened perceived performance, focused effort, and reduced frustration levels when engaging with AR-PaperSync. The average NASA-TLX score for AR-PaperSync stands at 18, underscoring a comprehensive enhancement in cognitive load metrics compared to the baseline, which was noted at 46. Further reinforcing this, a paired-sample t-test robustly confirms that the overall cognitive load is markedly lower for AR-PaperSync compared to the baseline *(t-statistic* $=$ *-16.51,* $p < 0.001$*).* Individual TLX subscales further highlight AR-PaperSync's effectiveness in diminishing mental *(t-statistic* $=$ *-9.85,* $p < 0.001$*)*, performance *(t-statistic* $=$ *-8.60,* $p < 0.001$*)*, and frustration *(t-statistic* $=$ *-8.40,* $p < 0.001$*).* Detailed NASA-TLX subscale scores are visually presented in Figure 6.3 for comprehensive insight.

System Usability. Our evaluation extended to assessing the system's usability, as quantified through the System Usability Scale (SUS). The results painted a striking picture of user satisfaction and ease of use when engaging with AR-PaperSync. Impressively, AR-PaperSync garnered substantially higher SUS scores compared to the baseline. These elevated scores indicate a system that users found remarkably intuitive and efficient. The average SUS score for AR-PaperSync reached an impressive high of 78, more than 59% of the baseline score, underscoring the system's user-friendly

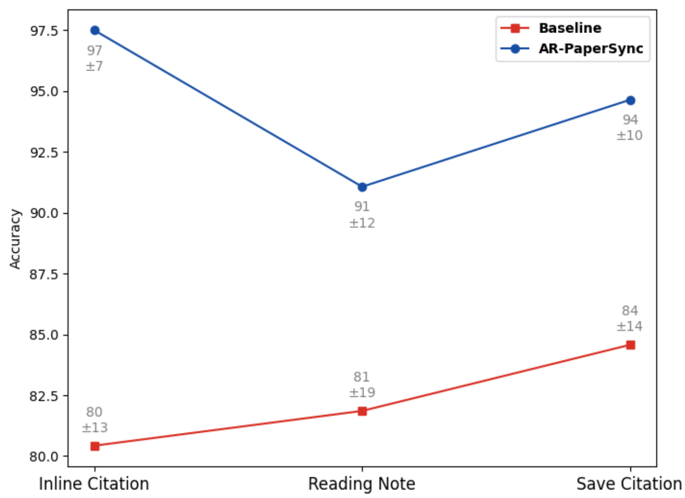


Figure 6.2. Performance comparison between AR-PaperSync and baseline in various task categories, including inline citations, saving citations, and reading notes

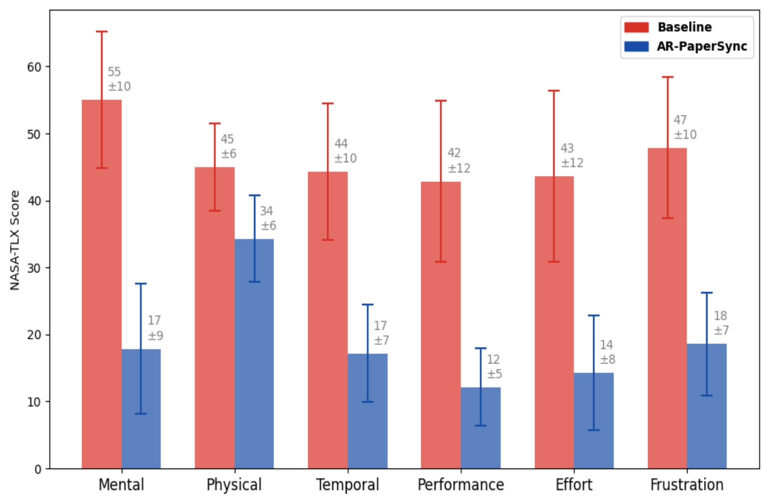


Figure 6.3. NASA-TLX subscale scores for AR-PaperSync and baseline comparisons.

nature and aligning with the positive findings related to task performance. The paired-sample t-test results further confirm the significant difference, with AR-PaperSync surpassing the baseline in terms of system usability *(t-statistic = 10.21, p < 0.001)*. A visual representation of the SUS score comparison is thoughtfully presented in Figure 6.4.

6.2. Qualitative Evaluation

Usefulness and Impact of AR-PaperSync Features. The feedback from participants demonstrates their appreciation of how AR-PaperSync has enriched their reading experience, offering significant practical advantages. The positive reception of AR-PaperSync's features is striking, with 89% of respondents affirming its usefulness. Key terms that frequently emerged in participants'

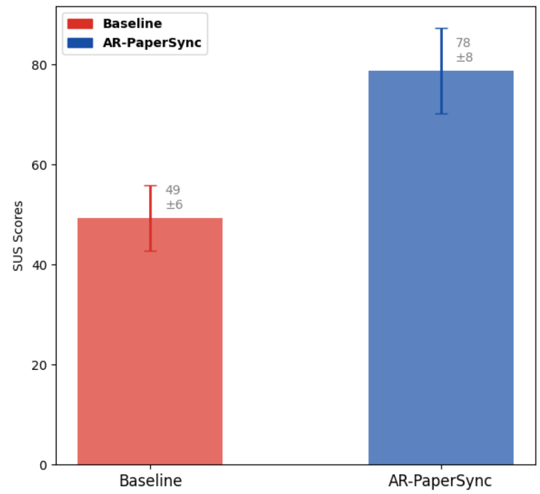


Figure 6.4. Comparison of System Usability Scale (SUS) Scores for AR-PaperSync and Baseline.

comments about AR-PaperSync's benefits include *"useful"*, *"good"*, *"greatly enhanced"*, *"easier"*, *"excellent"*, *"fast"*, and *"surprised"*. Specifically, Participant P9 effectively summarized the core benefit: *"Saves significant time and effort in locating papers"*. P1 highlighted its practical utility: *"Extremely useful for marking and annotating papers, offering time savings over traditional methods"*. Participants P14 and P13 expressed a sense of wonder, noting, *"The experience was delightful, especially being surprised by the appearance of citations on printed paper"*, and *"It seamlessly integrates my online annotations for quick access via AR"*. The interaction with AR-PaperSync is likened to using a dynamic app instead of paper. *"Interacting with citations in AR was akin to engaging with a physical paper"*, and *"It substantially enhances digital engagement with printed materials"*, observed P2 and P5, indicating a blurring of the lines between physical and digital paper. The ease of navigating citations was also a focal point. P8 and P3 noted the efficiency advantage: *"Allows rapid checking of citations"* and *"Significantly speeds up the process of reading physical papers"*. Meanwhile, P6 praised the visual features: *"The system operates swiftly, making citations visible and easy to save"*. This collective feedback suggests that AR-PaperSync effectively tackles some of the most labor-intensive aspects of academic research, particularly in managing extensive bibliographies and notes.

Future Adoption and Use Intentions. User feedback regarding AR-PaperSync distinctly indicates a strong inclination toward future adoption and continued utilization of the system's features. Remarkably, a substantial 93% of respondents affirmed their intent to utilize at least one feature offered by this tool in the future. Among these respondents, 74% expressed a keen interest in employing inline citations, 52% were inclined towards using reading notes, and 42% considered saving citation features appealing and practical. Notably, the sentiment was overwhelmingly positive, with P1 stating, *"I like inline citations and add comments option"*. This sentiment reverberated throughout several participants' responses, with one participant outlining a specific use case: *"I find inline citation feature helpful during literature reviews when I need to refer back to the reference paper"*. Even users who prefer digital media expressed openness to incorporating physical media into their workflow, thanks to AR-PaperSync. P3 commented, *"I typically use digital media, but I can see myself embracing physical media with this application"*. This highlights the system's potential to bridge the gap between digital and physical reading preferences. Furthermore, P5, P7, P12, and P14 emphasized the practicality and usefulness of AR-PaperSync features, such as marking read citations, adding comments, saving citations, and quickly accessing in-text citations in printed materials. These features were perceived as valuable for both current and future research endeavors. Overall, the user responses suggest a high likelihood of future adoption and continued use of AR-PaperSync, indicating that it can significantly impact and enhance reading and research practices.

Enhancements and Feature Requests. Collecting feedback on desired additional functionalities, P9 suggested *"Making open-source cited paper available with one click"*, indicating a need for streamlined access to resources. P10 envisioned more comprehensive integration: *"I wish to read cited papers remotely after saving, without having them with me"*, hoping for a feature allowing access to saved citations and notes beyond the immediate physical space. While the feedback was overwhelmingly positive, participants suggested improvements, such as increasing the app's speed and introducing different functionalities.

7. DISCUSSION

We discuss the implications of the AR-PaperSync study results, providing a detailed comparison of AR-PaperSync's performance against the baseline, particularly highlighting the system's efficiency, accuracy, cognitive load, system usability, and the insights gathered from user feedback.

7.1. Bridging the Physical-Digital Divide

The prevailing preference for printed materials over digital formats, as underscored by prior research [35, 17, 16] and our interviews, is rooted in their ability to foster better comprehension, enhanced retention, and more engaged reading. However, while digital tools have advanced in providing improved navigation and interactivity, they have fallen short of fully integrating the tactile benefits of printed materials with the convenience of digital enhancements [38, 8, 29, 12]. AR-PaperSync emerges as a groundbreaking solution to this enduring challenge, bridging printed papers' tactile engagement with the dynamic capabilities of digital tools. Our study's findings demonstrate that AR-PaperSync not only maintains but significantly enriches the traditional reading experience by overlaying augmented reality directly onto physical documents. Participants (P2, P3, P5, P7, P13) specifically noted that the AR view effectively links the printed paper with its digital counterpart, transforming the paper into an interactive application. This innovative approach enables users to seamlessly access digital functionalities—including inline citations, comprehensive bibliographic details, saved citations, and synchronized reading notes—without compromising the physical interaction cherished in printed materials. This seamless melding of printed and digital realms signifies a critical evolution in academic research tools, adeptly uniting the in-depth engagement of print reading with the expansive utility of digital resources.

7.2. Efficiency and Accuracy in Accessing Information

A significant challenge identified through our interviews was the manual tracking of inline citations, managing saved references, and notating insights on printed materials. These tasks, inherently time-intensive and prone to inaccuracies, significantly hinder the research workflow. In academic research, where efficiency in information retrieval and data reliability are critical, overcoming these obstacles is paramount.

Our study's quantitative analysis robustly validating hypothesis 1 showcases AR-PaperSync's significant advancements in the efficiency and accuracy of accessing information, markedly outperforming traditional baseline methods. Participants using AR-PaperSync completed tasks 90% faster on average than the baseline system, reducing the time for finding inline citations from 30 seconds to just 9 seconds. This improvement is critical in academic research, where every moment is valuable. Additionally, AR-PaperSync users demonstrated a remarkable 97% accuracy rate in identifying inline citations, substantially increasing from the 80% observed with baseline methods. This heightened accuracy is crucial, as it bolsters researchers' confidence in the system, ensuring they can rely on AR-PaperSync for precise and reliable information retrieval. Participants (P2, P6, P9, P11) reported that finding and managing citations became significantly quicker due to the ability to access citations and references directly from the printed document. The augmented reality overlay projecting digital citations onto physical papers streamlines the verification process of citations and enhances users' confidence in their research accuracy. This direct interaction with digital enhancements on a tangible medium ensures that researchers always engage with the correct references.

One of AR-PaperSync's most groundbreaking features is its real-time synchronization of reading notes across mobile, desktop, and printed formats. This capability addresses the continuity challenge between digital and physical environments, a concern frequently mentioned by researchers during interviews. While previous systems have introduced digital annotations or augmented reality experiences, they often operate in isolation, detached from the researcher's comprehensive workflow and reliant on disparate tools such as pens, tabletops, or projectors [10, 21, 14]. Unlike these systems, AR-PaperSync's cross-device interaction technology ensures that any notes made on a digital platform are instantly and accurately mirrored on the corresponding physical document. Moreover, the user study we conducted indicates significant gains in accuracy and efficiency for reading notes tasks with AR-PaperSync, observing an 11 to 20% increase in accuracy and a 30 to 40% reduction in completion time compared to baseline methods. Participants (P1, P6, P13) reported enhanced workflow speed and effectiveness, praising our mobile app for keeping their comments secure and readily accessible, eliminating the worry of information loss associated with traditional note-taking methods.

In contrast, participants utilizing traditional methods often resorted to duplicating their efforts, taking notes on digital devices and printed materials using sticky notes or direct annotations. This redundant process increased the likelihood of losing important information and consumed valuable time. AR-PaperSync, however, facilitates the viewing of reading notes directly on printed materials via the AR view, ensuring no information is lost and significantly enhancing the efficiency of the research process.

7.3. Reduction in Cognitive Load and Enhanced System Usability

AR-PaperSync significantly contributes by effectively reducing the cognitive load on researchers and enhancing the system's usability. The findings from our user study, including the lower NASA-TLX scores and higher SUS scores among AR-PaperSync users, robustly confirm hypothesis 2. Participants reported substantially lower cognitive load scores, with an average NASA-TLX score of 18 compared to the baseline's 46. This reduction in cognitive load can be attributed to the streamlined nature of AR-PaperSync, which simplifies tasks such as finding inline citations, managing references and reading notes.

During the user study, participants using traditional methods (group 2) were observed to rely on manual processes for tasks like finding inline citations and cross-referencing information between physical and digital sources. This division of attention during research tasks often led to increased cognitive load. In contrast, participants using AR-PaperSync (group 1) could focus their mental resources on comprehension and synthesis, as the system facilitated seamless information retrieval and management. By reducing cognitive load, AR-PaperSync makes the reading process more efficient and enhances overall engagement with the material, potentially leading to deeper insights and better research outcomes.

Moreover, the high System Usability Scale (SUS) score of 78, significantly higher than the baseline, underscores users' positive perceptions of AR-PaperSync's usability. Participants highlighted the system's user-friendly interface, with user comments (e.g., P4, P10) indicating that AR-PaperSync is intuitive and easy to navigate. This ease of use is crucial for adopting new technologies in research settings, as it can substantially enhance the efficiency and productivity of academic work.

7.4. Improvement in Reading Experience

The qualitative feedback collected closely aligns with hypothesis 3, affirming that AR-PaperSync substantially enhances the reading experience of printed scientific papers. Participants expressed appreciation for the system's practical advantages, frequently using terms like *"useful," "efficient," "easier,"* and *"greatly enhanced."* For instance, Participant P9 noted significant time and effort lowering in finding papers, while Participant P1 commended the system for marking and annotating papers more efficiently than traditional methods. Participants P14 and P13 expressed delight and surprise upon seeing how citations appeared on printed paper through AR view, the novel experience AR-PaperSync offers.

Moreover, participants appreciated the system's ability to blend digital engagement with physical materials seamlessly. Observations from participants P2 and P5 underscored AR-PaperSync's effectiveness in this regard. As noted by Participants P8 and P3, the ease of navigating citations and the swift access to the citation details on printed paper, highlighted by Participant P6, further emphasize AR-PaperSync's efficacy in addressing the labour-intensive aspects of academic research.

AR-PaperSync not only streamlines the reading process but also enhances engagement and efficiency. By seamlessly integrating augmented reality interactions, the system introduces dynamic elements to the traditional reading experience, making it more interactive and stimulating. These user experiences underscore AR-PaperSync's capacity to enrich educational reading practices, ultimately enhancing the overall research endeavour.

8. CONCLUSION AND FUTURE WORKS

8.1. Conclusion

AR-PaperSync, an innovative augmented reality system, significantly advances the integration of digital technology with traditional academic reading practices. Through its intuitive design and functionality, AR-PaperSync has demonstrated its usefulness in streamlining the management of citations and reading notes in printed scientific papers. Our user study results indicate that AR-PaperSync enhances efficiency, accuracy, and system usability in accessing information and significantly reduces cognitive load, thereby transforming the traditional academic reading experience into a more engaging and efficient process. The system's ability to seamlessly blend printed papers' physical tangibility with the dynamic interactivity of digital tools represents a notable contribution to educational technology and academic research tools.

8.2. Future Works

In future iterations of AR-PaperSync, we plan to harness the capabilities of Machine Learning (ML) and deep learning to enhance the system's functionality and user experience significantly [27, 26, 25, 24, 23]. We will integrate a feature to access all inline citations of a paper with a single click on AR view addressing participant P9's feedback. In alignment with P10's vision, we will develop real-time synchronization of saved citations from printed paper to desktop, enabling remote access from any environment. To improve responsiveness, ML-driven optimization techniques will be employed to boost the application's speed. We also aim to expand our system with advanced NLP and deep learning techniques for deeper information extraction and automation, offering sophisticated content analysis and contextual insights. This strategic integration of ML and deep learning technologies is poised to transform AR-PaperSync into a more adaptive, efficient, and powerful tool, advancing its impact on academic research and educational technology.

REFERENCES

[1] Annette Adler, Anuj Gujar, Beverly L. Harrison, Kenton O'Hara, and Abigail Sellen. A diary study of work-related reading: Design implications for digital reading devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '98, page 241–248, USA, 1998. ACM Press/Addison-Wesley Publishing Co.

[2] Hamda Al-Ali, Mhd Wael Bazzaza, M. Jamal Zemerly, and Jason W. P. Ng. Myvision air: An augmented interactive reality book mobile application. In *2016 IEEE Global Engineering Education Conference (EDUCON)*, pages 741–745, 2016.

[3] Selma Albayrak and Rabia Meryem Yilmaz. An investigation of pre-school children's interactions with augmented reality applications. *International Journal of Human–Computer Interaction*, 38(2):165–184, 2022.

[4] Toshifumi Arai, Dietmar Aust, and Scott E. Hudson. Paperlink: A technique for hyperlinking from real paper to electronic content. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*, CHI '97, page 327–334, New York, NY, USA, 1997. Association for Computing Machinery.

[5] Faruk Arici. Investigating the effectiveness of augmented reality technology in science education in terms of environmental literacy, self-regulation, and motivation to learn science. *International Journal of Human–Computer Interaction*, 0(0):1–21, 2024.

[6] Andrea Bianchi, So-Ryang Ban, and Ian Oakley. Designing a physical aid to support active reading on tablets. CHI '15, page 699–708, New York, NY, USA, 2015. Association for Computing Machinery.

[7] Mark Billinghurst, Hirokazu Kato, and Ivan Poupyrev. The magicbook-moving seamlessly between reality and virtuality. *IEEE Computer Graphics and applications*, 21(3):6–8, 2001.

[8] Joseph Chee Chang, Amy X. Zhang, Jonathan Bragg, Andrew Head, Kyle Lo, Doug Downey, and Daniel S. Weld. Citesee: Augmenting citations in scientific papers with persistent and

personalized historical context. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, CHI '23, New York, NY, USA, 2023. Association for Computing Machinery.

[9] Min Fan, Yichen Wu, Jianyu Fan, Xinyue Cui, and Sitong Lin. Character alive: Designing and evaluating a tangible system to support children's chinese radical and character learning. *International Journal of Human–Computer Interaction*, 0(0):1–16, 2024.

[10] François Guimbretière. Paper augmented digital documents. In *Proceedings of the 16th annual ACM symposium on User interface software and technology*, pages 51–60, 2003.

[11] Han L. Han, Junhang Yu, Raphael Bournet, Alexandre Ciorascu, Wendy E. Mackay, and Michel Beaudouin-Lafon. Passages: Interacting with text across documents. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22, New York, NY, USA, 2022. Association for Computing Machinery.

[12] Andrew Head, Kyle Lo, Dongyeop Kang, Raymond Fok, Sam Skjonsberg, Daniel S Weld, and Marti A Hearst. Augmenting scientific papers with just-in-time, position-sensitive definitions of terms and symbols. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–18, 2021.

[13] Andrew Head, Amber Xie, and Marti A Hearst. Math augmentation: How authors enhance the readability of formulas using novel visual design practices. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, pages 1–18, 2022.

[14] David Holman, Roel Vertegaal, Mark Altosaar, Nikolaus Troje, and Derek Johns. Paper windows: Interaction techniques for digital paper. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '05, page 591–599, New York, NY, USA, 2005. Association for Computing Machinery.

[15] Zheng Huang and Jun Kong. A toolkit for prototyping tabletop-centric cross-device interaction. *International Journal of Human–Computer Interaction*, 36(6):536–552, 2020.

[16] Yu-Cin Jian. Reading in print versus digital media uses different cognitive strategies: evidence from eye movements during science-text reading. *Reading and Writing*, 35(7):1549–1568, 2022.

[17] Xiaoming Yang Jie Yu, Xing Zhou and Jie Hu. Mobile-assisted or paper-based? the influence of the reading medium on the reading comprehension of english as a foreign language. *Computer Assisted Language Learning*, 35(1-2):217–245, 2022.

[18] Hyeonsu B Kang, Rafal Kocielnik, Andrew Head, Jiangjiang Yang, Matt Latzke, Aniket Kittur, Daniel S Weld, Doug Downey, and Jonathan Bragg. From who you know to what you read: Augmenting scientific recommendations with implicit social networks. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22, New York, NY, USA, 2022. Association for Computing Machinery.

[19] Dae Hyun Kim, Enamul Hoque, Juho Kim, and Maneesh Agrawala. Facilitating document reading by linking text and tables. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, page 423–434, New York, NY, USA, 2018. Association for Computing Machinery.

[20] Tereza Gonçalves Kirner, Fernanda Maria Villela Reis, and Claudio Kirner. Development of an interactive book with augmented reality for teaching and learning geometric shapes. In *7th Iberian Conference on Information Systems and Technologies (CISTI 2012)*, pages 1–6. IEEE, 2012.

[21] Motoki Kobayashi and Hideki Koike. Enhanceddesk: integrating paper documents and digital documents. In *Proceedings. 3rd Asia Pacific Computer Human Interaction (Cat. No. 98EX110)*, pages 57–62. IEEE, 1998.

[22] Zhangyu Meng, Jun Kong, and Juan Li. Utilizing binary code to improve usability of pressure-based authentication. *Computers & Security*, 103:102187, 2021.

[23] Md Ochiuddin Miah, Umme Habiba, and Md Faisal Kabir. Odl-bci: Optimal deep learning model for brain-computer interface to classify students confusion via hyperparameter tuning. *Brain Disorders*, 13:100121, 2024.

[24] Md Ochiuddin Miah, Al Maruf Hassan, Khondaker Abdullah Al Mamun, and Dewan Md Farid. Brain-machine interface for developing virtual-ball movement controlling game. In

Proceedings of International Joint Conference on Computational Intelligence, pages 607–616. Springer, 2020.

[25] Md Ochiuddin Miah, Sakib Shahriar Khan, Swakkhar Shatabda, and Dewan Md. Farid. Improving detection accuracy for imbalanced network intrusion classification using cluster-based under-sampling with random forests. In *1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT 2019)*, pages 1–5, Dhaka, Bangladesh, May 2019.

[26] Md Ochiuddin Miah, Sakib Shahriar Khan, Swakkhar Shatabda, Khondaker Abdullah Al Mamun, and Dewan Md. Farid. Real-time eeg classification of voluntary hand movement directions using brain machine interface. In *The IEEE Region 10 Symposium (TENSYMP 2019) Symposium Theme: Technological Innovation for Humanity*, pages 534–539, Kolkata, India, June 2019.

[27] Md Ochiuddin Miah, Rafsanjani Muhammod, Khondaker Abdullah Al Mamun, Dewan Md Farid, Shiu Kumar, Alok Sharma, and Abdollah Dehzangi. Clusem: Accurate clustering-based ensemble method to predict motor imagery tasks from multi-channel eeg data. *Journal of Neuroscience Methods*, 364:109373, 2021.

[28] Michael Nebeling and Katy Madier. 360proto: Making interactive virtual reality & augmented reality prototypes from paper. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, page 1–13, New York, NY, USA, 2019. Association for Computing Machinery.

[29] Sangjun Park, Chanhee Lee, and Uichin Lee. Quickref: Should i read cited papers for understanding this paper? In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, CHI EA '23, New York, NY, USA, 2023. Association for Computing Machinery.

[30] Antoine Ponsard, Francisco Escalona, and Tamara Munzner. Paperquest: A visualization tool to support literature review. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '16, page 2264–2271, New York, NY, USA, 2016. Association for Computing Machinery.

[31] Brett Powley, Robert Dale, and Ilya Anisimoff. Enriching a document collection by integrating information extraction and pdf annotation. In *Document Recognition and Retrieval XVI*, volume 7247, pages 47–56. SPIE, 2009.

[32] Jing Qian, Qi Sun, Curtis Wigington, Han L. Han, Tong Sun, Jennifer Healey, James Tompkin, and Jeff Huang. Dually noted: Layout-aware annotations with smartphone augmented reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22, New York, NY, USA, 2022. Association for Computing Machinery.

[33] Shwetha Rajaram and Michael Nebeling. Paper trail: An immersive authoring system for augmented reality instructional experiences. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22, New York, NY, USA, 2022. Association for Computing Machinery.

[34] Rufat Rzayev, Polina Ugnivenko, Sarah Graf, Valentin Schwind, and Niels Henze. Reading in vr: The effect of text presentation type and location. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, CHI '21, New York, NY, USA, 2021. Association for Computing Machinery.

[35] Nallainathan Senthuran, Indang Ariati Binti Ariffin, Ali Khatibi, and Jacquline Tham. Impact on exam performance of undergraduates when learning through print books vs e-books. *Journal of Positive School Psychology*, 7:323–336, 2023.

[36] Jurgen Steimle, Oliver Brdiczka, and Max Muhlhauser. Coscribe: integrating paper and digital documents for collaborative knowledge work. *IEEE Transactions on Learning Technologies*, 2(3):174–188, 2009.

[37] Craig S. Tashman and W. Keith Edwards. Active reading and its discontents: The situations, problems and ideas of readers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, page 2927–2936, New York, NY, USA, 2011. Association for Computing Machinery.

[38] Craig S. Tashman and W. Keith Edwards. Liquidtext: A flexible, multitouch environment to support active reading. In *Proceedings of the SIGCHI Conference on Human Factors in*

Computing Systems, CHI '11, page 3285–3294, New York, NY, USA, 2011. Association for Computing Machinery.

[39] Lili Wang, Xiangyu Li, Jian Wu, Dong Zhou, Im Sio Kei, and Voicu Popescu. Avicol: Adaptive visual instruction for remote collaboration using mixed reality. *International Journal of Human–Computer Interaction*, 0(0):1–20, 2024.