Hybrid Paper-Digital Interfaces: A Systematic Literature Review

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ABSTRACT

Past research recognized that paper has many advantages over digital devices, such as affordability, tangibility, and flexibility. Paper, however, also lacks many of the functionalities available in digital technologies, such as access to online resources and the ability to display interactive content. Prior research therefore identified opportunities for fusing the two mediums into a combined interface. This work presents a literature review on this form of innovation - technologies that bridge the paper-digital gap. First, we synthesize an understanding of paper and its relationship with digital devices through the lens of past works. Then, we outline the state-of-the-art for paper-digital interfaces and highlight possible use cases and implementation approaches. Last, we discuss design considerations and future work for developing paper-digital interfaces. Our work may be beneficial for HCI researchers interested in the development of hybrid paper-digital interfaces, and more broadly in embedding digital functionalities in everyday objects.

CCS CONCEPTS

• General and reference → Surveys and overviews; **• Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

paper interfaces, paper computing, interactive paper

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1 INTRODUCTION

> *"At breakfast Sal reads the news. She still prefers the paper form, as do most people. She spots an interesting quote from a columnist in the business section. She wipes her pen over the newspaper's name, date, section and page number and then circles the quote. The pen sends a message to the paper, which transmits the quote to her office."*
>
> - Mark Weiser, 1991 [80]

Despite the advent of computing, paper remains prevalent in our everyday life [67]. Many researchers have tried to explain its sustained use [9, 24, 43, 66, 67, 75]; to them, paper's ubiquitous status is both a curiosity and an opportunity. Within the HCI research community, interest persists in weaving computational capabilities into paper to produce more natural user interfaces [42, 82]. Prior work has recognized that physical paper and digital devices have complementary "profiles of strengths and weaknesses" [55]. On the one hand, paper is more convenient to annotate, easier to navigate with tactile input, and provides a larger, less costly, and higher-resolution display surface, but it is static and expensive to duplicate, distribute, and archive [22]. On the other hand, digital devices make operations like sharing, indexing, and saving contents effortless, but lack desirable properties, such as physical flexibility [22, 42]. As a result, past research has argued the benefits of implementing interfaces that combine the affordances of both mediums [67].

Over the past three decades, HCI researchers explored combinations of paper and computational functionalities in domains ranging from air traffic control [49] to medical record keeping [29]. The earliest work on "closing the gap between paper and digital information spaces" enabled users to interact with electronic objects projected on physical paper documents with their fingers [81]. More recent examples include book-based interfaces for controlling public displays [84] and mobile applications that overlay quantitative insights on physical affinity diagrams [73].

This paper presents a systematic literature review of this body of research. In addition to the clear continued relevance of this topic, our work is motivated by two observations. First, this accumulating collection of works addresses a wide range of application domains and tends to favor the implementation of new prototypes. Building upon this diverse body of knowledge presents potential challenges for researchers. For instance, the lack of consolidated knowledge results might lead to unnecessary duplication in research. Similarly, concrete design guidelines might be difficult to extract from this disjointed collection of existing works.

Second, many works predate modern technologies which have made embedding digital functionalities in everyday objects easier. An example is development in augmented reality technologies, like the Microsoft HoloLens, which enables high fidelity gesture recognition and object tracking, as utilized in Li et al.'s HoloDoc system [42]. Likewise, off-the-shelf camera and image processing software has empowered the development of more robust prototypes, such as Subramonyam et al.'s Affinity Lens application [73]. With newly available innovations that have only recently been exploited in this domain, we anticipate a spike of interest for integrating digital functionalities in physical paper.

For the sake of clarity and concision, we adopt the term *hybrid paper-digital interface* to refer to the innovations targeted in this review. We define a hybrid paper-digital interface as any interface embedding digital or electronic functionality in physical paper to enable its use as an input or output device. Example innovations include automatically digitizing touch input on paper to access supplemental content from the internet [42] and introducing multimedia content to paper displays [28]. Prior research has applied input devices ranging from digital pens to RFID, and output devices including projections and mobile phones. Our definition of hybrid paper-digital interfaces excludes the class of works embedding physical actuation mechanisms in paper for the sole sake of motion (e.g., movable paper crafts).

In this paper, we present results from a review of 60 papers from 13 HCI-related venues. We create an overview of past works to inspire, support, and expedite further studies in the development of hybrid paper-digital interfaces. Our review seeks to answer the following research questions (RQ):

RQ1: What are the capabilities and limitations of paper, and how do they align with the capabilities and limitations of digital devices?

RQ2: In what contexts are hybrid paper-digital interfaces applicable?

RQ3: What are the strategies for bridging the paper-digital gap?

RQ4: What are the design considerations for guiding the development of hybrid paper-digital systems?

2 BACKGROUND

Our concept of hybrid paper-digital interfaces was inspired by many works, particularly of Wellner [82], Mackay and Fayard [48], and Kaplan and Jermann [33]. Wellner was one of the first researchers to propose the idea of enhancing paper "with computation" instead of replacing it entirely [82]. Mackay and Fayard proposed *interactive paper* - user interfaces that offer "the best aspects of both physical paper and electronic documents" [48]. Kaplan and Jermann adopt the term *paper computing* to refer to the same innovations, namely "projects that explore the role of paper documents as interfaces to our digital world" [33]. As evidenced by Mackay and Fayard [48] and Kaplan and Jermann [33], numerous interchangable expressions have previously described technologies we define as hybrid paper-digital interfaces. We make note of the following: *augmented paper*, *interactive paper*, *paper computing*, *paper-based computing*, *paper interface*, and *paper-based interface* [4, 32, 33, 48, 69].

The topic of hybrid paper-digital interfaces falls under the research theme of weaving computational capabilities into everyday objects [1, 16]. Paper is among the "everyday objects" explored by researchers bridging the gap between virtual and physical spaces [8, 21]. Paper is a tactile medium, so hybrid systems involving it may be considered tangible user interfaces [31]. As in Ishii and Ullmer's vision of "tangible bits," one key feature of hybrid paper-digital interfaces is exploiting the user's existing skills for processing information by interacting with physical objects [31]. Our hybrid paper-digital interfaces is additionally related to prior concepts of organic, self-actuated, and shape-changing interfaces [27, 65]. However, we distinguish our work from prior research on movable paper craft technology [61, 86, 87]. Our definition excludes systems that embed physical actuation mechanisms in paper for the sole sake of motion.

A wealth of comprehensive surveys on related themes, like ubiquitous computing [1], tangible user interfaces [30, 68], organic user interfaces [27], and shape changing technologies [63], currently exist, but a meta-analyses of works on specifically hybrid paper-digital interfaces is lacking. Earlier systematic reviews and studies were either dated or domain specific [46, 59]. We exclude related works on interactive paper crafts from our review because most work in that domain focuses on enabling physically actuated dynamic behaviors instead of closing the gap between paper and digital affordances. The topic is additionally already well reviewed in HCI research [61, 86, 87].

3 METHOD

Adopting a similar approach to [5] and [11], we began consolidating prior research on bridging the paper-digital gap by curating a corpus of related papers. Using the ACM Digital Library, IEEE Xplore, Scopus, Taylor & Francis, SpringerLink platforms, we sampled for potentially relevant literature with the following search terms: *paper interface*, *paper computing*, *interactive paper*, *augmented paper*, *paper-based interface*. We obtained the terms using the seed keywords *paper interface*, *interactive paper*, and *paper computing* and expanding our list of search terms as we encountered other relevant descriptors. We focused our search on the top twenty HCI venues listed in the Google Scholar Ranking (i.e., CHI, CSCW, UbiComp, UIST, IEEE ToAC, HRI, IJHCS, IEEE ToHMS, BIT, DIS, ICMI, IJHCI, TOCHI, HCI International, Mobile HCI, IEEE ToH, IUI, ASSETS, TEI, UMAP). Additionally, we included the proceedings of the ISS (formerly ITS), PerDis, and MM conferences. ISS and PerDis are included because one research direction pertaining to our theme involves extending paper into either an interactive surface or pervasive computing device. We included the proceedings of MM for a multimedia perspective. The search was done in June 2020 and yielded a selection of 254 papers.

We subsequently filtered out works from companion or adjunct proceedings, as well as short articles, posters, books, and theses. We additionally defined two inclusion criteria: (1) articles must present a novel prototype or systems in which paper is augmented or used as an artifact to bridge the paper-digital divide; articles purely presenting study results, for instance, are excluded, and (2) the role of paper must be central to the presented system. Inclusion criteria (1) is defined because study-oriented works often do not provide insight into concrete solution implementations. Inclusion criteria (2) is defined to filter works that are concerned the general field of tangible user interfaces [38] or use paper purely for tracking purposes [56], since such work does not contribute to answering our defined research questions.

Applying the eligibility requirements to our initial results narrowed our corpus to 45 entries. We discovered 13 additional works by reference crawling the filtered results. We later added two sources from the CHI 2020 proceedings that present contributions relevant to the scope of our review. Our final corpus contains 60 sources, published between 1992 and 2020 in 13 venues (Fig. 1).[1]

We begin our analysis by familiarizing ourselves with the corpus. From our preliminary reading, in a similar manner to [6], we develop a set of questions to summarize each work and scaffold comparison and consolidation of the findings. The questions describe salient aspects addressed by most works in our corpus. We derived these questions comparative discussion. The questions are deemed sufficiently descriptive all works, as well as insightful to the high-level goals of the literature review. The questions are as follows: (1) what are the core research questions addressed by the work? (2) what motivates the work? (3) how does the work understand the usages, capabilities, and limitations of paper? (4) what is the target application domain of the work? (5) what are some proposed extensions to paper proposed by the work? (6) what design constraints or objectives guided the work's implementation of the proposed extensions? (7) how are the proposed extensions implemented? (8) what findings have been obtained from either the implementation process or the evaluation of the proposed system?

The remainder of our work is organized as follows. First, we present a consolidated understanding of paper and its relationship with digital technologies through the lens of past works. Second, we identify potential use cases for hybrid paper-digital technologies. Third, we highlight the most salient approaches used by works in our corpus to bridge the paper-digital gap. Fourth, we present a list of design considerations for hybrid paper-digital interfaces. We conclude by recommending directions for future work and discussing the limitations of our review.

4 UNDERSTANDING PAPER

We began by examining at how past research understands paper's characteristics and relationship with digital technologies. We identified four salient themes relating to the impact of modern computing on perceptions of various paper properties. The results from this section build upon the findings of past works that seek to explain the persistence of paper use (e.g., [67]). In many instances, past work was motivated and guided by the inherent characteristics of paper. By unpacking these themes, we aim to inform readers of paper properties commonly targeted for integration.

4.1 Ubiquity and Tangibility

Paper's ubiquity and tangibility are perceived as advantageous throughout our corpus [2, 7, 12–14, 17, 20, 26, 34, 36, 39, 41, 42, 50, 54, 71, 72, 74, 88]. The ubiquity of paper usage is often framed as a characteristic antithetical to developments in computing [42, 64]. Klemmer et al., Zhang and Harrison, and Giraudeau et al. all attribute paper's ubiquity, in part, to the low cost and availability of the medium [20, 37, 85]. In certain practices, extensive historical use has rendered paper inseparable from the workflow [15, 49]. For example, in financial advisory consultations, paper usage has become embedded in the ritual of client meetings [15]. In air traffic control, the use of paper flight strips shapes the practitioner's mental representation of the task [49]. Paper's current status as a medium is precisely what Mark Weiser envisioned for the future of computing. It effortlessly surrounds us in everyday life [80]. Researchers therefore saw opportunities in adapting the medium into a user interface, hoping to piggyback on its already ubiquitous status.

As an inherently physical medium, paper affords tangible interactions. Tangibility is long considered as lacking in digital documents [54]. Some researchers, like Klemmer et al., have therefore proposed using paper to make information tangible again [39]. Gupta et al. have found that users both enjoy and place a substantial amount of value on the physical experience of interacting with printed media objects [23]. As established by Ishii and generally accepted by the HCI research community [31], sensing and manipulating physical objects is a skill that people inherently have. Researchers therefore sought to exploit paper's natural haptic qualities in developing new hybrid interfaces.

4.2 Flexibility

Throughout our corpus, we recognize substantial discussion on the flexibility of paper [10, 28, 28, 36, 42–45, 51, 60, 77, 83]. Like ubiquity, the flexibility of paper is often highlighted in contrast to the capabilities of digital devices. Paper is regarded as flexible from two perspectives: spatially and as a holder of information. As individual entities, paper objects can be folded, cut, rotated, and moved in space along many degrees of freedom [28, 42, 44, 45]. As a collection of entities, paper objects are naturally reconfigurable as multi-object spatial layouts [42, 51]. This capability is exploited to perform tasks like grouping and clustering [73] and multi-document comparisons [47]. Some researchers also conceptualize paper as an infinitely extendable and reconfigurable display and input space [47, 64].

Paper is also remarkably versatile, supporting freeform capture and representation of information [10, 28, 36, 43, 51, 60, 77, 83]. Markings on paper objects can be arbitrarily complex and personalized [19], which makes it a better medium for supporting nonlinguistic and spatial information. In the context of music composition, enabling free associations between markings and mental model is essential (i.e., a direct link between human gesture and idea) [77]. The ability to freely highlight, annotate, and sketch is likewise appreciated in the domain of biology [50]. Past work has recognized, however, that the flexibility of paper may not be advantageous for all tasks. Some amount of structure may be beneficial for sharing information, for instance in the form of a written report. Lack of structure also makes certain tasks, like creating tables, cumbersome [50]. Past researchers have regarded these limitations as opportunities to introduce digital enhancements. Integrating

[1] We open source our analysis in the following repository: https://github.com/ycheng14799/DIS2021HybridPaperDigital

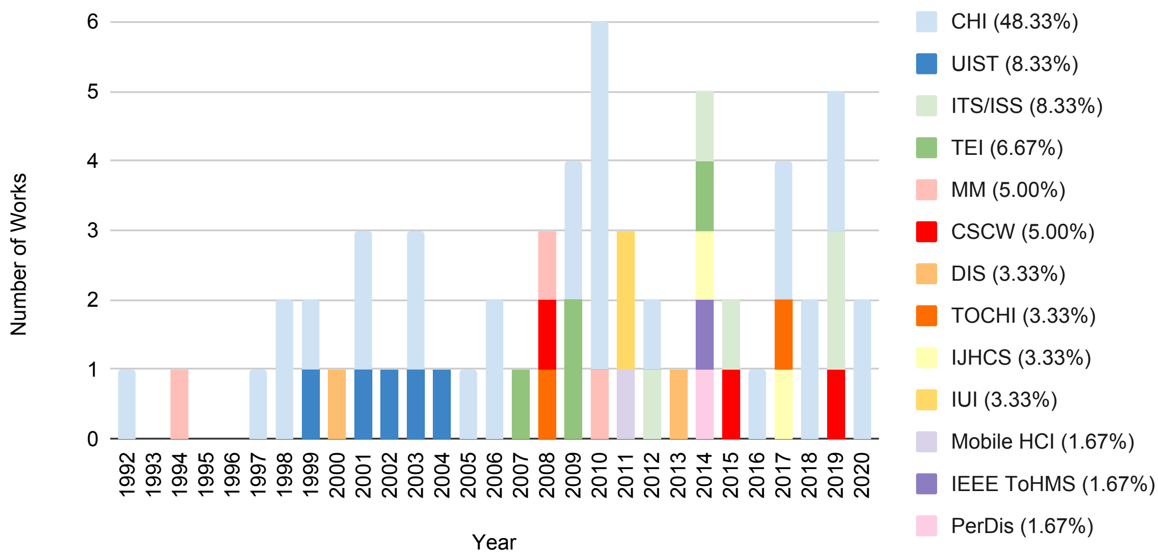

Figure 1: Number of works in our corpus by year and venue.

paper and digital technology can, for instance, potentially support tasks requiring structure while retaining the natural flexibility of physical paper.

4.3 Paper as a Static Medium

Paper is often recognized a static medium, incapable of providing the interactivity that digital devices afford [12, 22]. This property is primarily framed as a limitation [20, 22, 34, 85]. Researchers tend to argue that paper would benefit from greater interactivity, modifiability, and the ability to display dynamic content [20, 22, 34, 85]. Yet, such extensions may not always be desirable [7, 41, 60, 77]. In certain contexts, researchers have recognized the static nature of paper as an advantage [7, 41]. For instance, in music composition, paper is preferred because of its slow, low-impact, and static nature [77]. Likewise, Post-it notes are largely appreciated for their location sensitive, passive reminding [60]. The degree to which paper's static nature is a limitation is ultimately context dependent. This should be taken into consideration in the implementation of paper-digital interfaces.

4.4 Reliability and Permanence

The reliability and permanence of paper as a medium are aspects for which perception has changed over time. Paper was historically regarded as more durable and permanent compared to digital devices [77, 83, 85]. Ideas which informed this perspective include paper's independence from electrical power and ability to withstand physical abuse [83]. This perspective was enforced by associations of digital devices with software failures and digital media with impermanence [47, 77]. As a result, paper was often preferred for critical scenarios, like air traffic control [49]; mobile scenarios, like biology field research [83]; and as an archival medium [10, 74, 77]. Perceptions about the permanence of paper have changed due to the increased reliability of digital devices. Additionally, new digital technologies present benefits in managing increasing volumes of information. Digital solutions offer functionalities for organizing and navigating information, such as searching and indexing [3, 10, 22, 35, 42, 43, 45, 47, 50], version management [35, 39], and information sharing [3, 10, 13, 25, 35, 45]. They also occupy less space than paper when content is high in volume [67]. It is important to note that some information from paper is not necessarily persistent, like the spatial relationships between documents. In addition, due to the medium's low cost and availability, paper holds dual perception of ephemerality. The medium is, for instance, regarded as disposable, particularly in the context of design and ideation [79].

5 USE CASES

We identify three themes in our corpus relating to potential usage scenarios of paper-digital interfaces. In the following, we illustrate these use cases, aiming to support researchers in contextualizing their contributions. At least one of the three themes is applicable to each work we reviewed; some works may address multiple use cases.

5.1 Use Case: Updating Paper-based Practices

This subset of works investigates scenarios where conventional paper-based practices are no longer sufficient [23], but a wholly digital replacement cannot currently be implemented. The barriers to adopting a digital solution are manifold. One reason is that some affordances of paper (e.g., tangibility) are difficult to supplant [4]. The medium is sometimes so heavily embedded within a work practice that removing it would be impractical, at least in the short term [49]. Digital integration, as opposed to digital replacement, therefore represents a best of both worlds – properties of the original paper-based practice are preserved, with digital functionalities implemented to keep the practice up-to-date in face of new challenges such as big data and the increasing pervasiveness of remote work [17, 73].

The use case targeted in an early work by Mackay et al. is one example where a paper-based practice was outdated, but difficult to replace with technology [49]. In 1998 air traffic control, paper strips were used to direct flight paths [49]. Despite an need to improve this practice due to increasing flight traffic, attempts to replace paper flight strips with new computer systems were ineffective [49]. The role of paper was so entangled in the user's mental model of the task that replacing paper with a digital system was infeasible at the time [49]. Similarly, the increasing importance of complex and mixed data in design has challenged practitioners' preference for physical sticky-notes [83]. Currently, designers are forced to choose between the physicality of sticky-notes and the analytical power of digital technologies [73]. The properties of physical post-it notes, including their ease of use, spatiality, and flexibility, are difficult to replace with a digital device [73]. Subramonyam et al. proposed using a mobile-AR solution to overlay quantitative insights on top of a physical affinity diagram setup [73].

Targeting this use case requires in-depth understanding of existing user practices, mental models, and challenges in the application domain. Neglecting the role of existing practices may yield unworkable solutions that will ultimately be rejected by end users.

5.2 Use Case: Enriching Interaction

Early works in our survey often focused on enabling users to access digital functionalities with lower requirements of computer literacy [49, 53] or supporting navigation of computer interfaces regarded as un-intuitive [69]. For instance, Signer et al.'s work specifically targeted past dissatisfaction with the PowerPoint laptop interface [69]. The proposed solution used Anoto Digital Pen technology to support more intuitive, convenient, and mobile control of a presentation through a printed slide-deck [69]. Over time, increasing computer literacy within the global population and improvements to digital user interfaces have reduced barriers to operating and navigating computer systems. Addressing this need is now less of a priority.

However, the principle of building accessible user interfaces with paper remains relevant. For instance, Pearson et al. explored the possibility of using paper-based interfaces to open access to digital services for resource-constrained communities [57]. They demonstrated the efficacy of combining paper with low-cost mobile phones in supporting information access via an interactive voice response system [57]. There are also benefits to using paper-based interfaces in contexts involving users with special needs. Alessandrini et al. demonstrated the effectiveness of a tailored paper-based interface for therapy with children on the autism spectrum [2].

Prior works also explored the potential of using paper to introduce richer and more engaging interactions. For instance, Zufferey et al. used paper as an interface between a tangible simulation and computer processes, as a tactile alternative to traditional GUI controls [88]. Likewise, Yoshino et al.'s system used a book to operate an public display in a museum [84]. They found the interface more engaging than purely digital displays due to the simultaneous novelty and familiarity of the interactions it afforded [84].

Designing for this use case involves identifying missing physical experiences that would allow users to take full advantage of technologies and better enjoy themselves in the process. Then designers must study how properties of paper could be exploited to actualize these experiences.

5.3 Use Case: Addressing Complications of Paper-Digital Coexistence

This final subset of works addresses complications arising from the coexistence of paper and digital solutions. Paper and digital tools can coexist in one of two ways: in parallel, meaning that they are used for different purposes in the same task; or as a redundancy, serving the same purpose in two mediums. In the early stages of music composition, for instance, paper is used to jot down quick ideas, while digital tools are used to record more developed ideas so they could be played back as audio. There is a constant need to transform information between the two mediums [77]. In the workflow for producing illustrations, practitioners are faced with the same problem. Switching from paper tools to software and vice versa is a manual process that is highly time-consuming [76, 77]. Introducing more integrated paper-digital interfaces is one proposed solution to this issue. In situations where paper and digital tools are used redundantly, inefficiencies arise from ensuring that the two formats are synchronized at all times. This issue is noted by Houben et al. in medical record keeping [29]. According to Tabard et al. in collaborative settings, which tend to be more dynamic, this issue is amplified [74]. Researchers saw potential in using paper-digital integration to mitigate issues related to redundancy across mediums [29].

Designing for the "paper-digital coexistence" use case involves identifying transition points in users' workflows, then streamlining the process. The reason for the coexistence of paper and digital tools in the environment or workflow must be critically considered. Usually, it is either due to requirements of law or custom, or because the mediums offer support for different tasks. In the latter case, the best aspects of both mediums should be identified and maximized.

5.4 Application Domains

Motivated by the aforementioned use cases, paper-digital interfaces have been explored in many application domains. The most prevalent domains mentioned in our corpus include: design, ideation, and creativity support (11 works), document-intensive analysis tasks (11 works), learning and education (6 works), note-taking (6 works), and presentation delivery (4 works). Minor domains range from high-touch advisory services [15] to data visualization [12].

6 IMPLEMENTATION APPROACHES

The key commonality between the works in our corpus is that they implement a link between paper and digital technologies. Bridging the two otherwise isolated mediums ultimately enables a set of new and unique interactions. In the following, we first discuss how the works we surveyed have bridged the paper-digital gap. Then, we highlight the new functionalities that this supports.

When looking at concrete approaches to bridging the paper-digital gap, three themes emerged from our analysis. They are (1) activating paper as an input device to the digital realm, (2) augmenting paper's output capabilities, and (3) cross-media content association. An overview of the implementation approaches is provided in Figure 2.

6.1 Paper as an Active Input Device

The first approach for bridging the paper-digital gap involves enabling more direct access and control of digital resources from paper entities. Works in our corpus have adopted the three following mechanisms to achieve this end:

6.1.1 Enabling "Active Regions". This mechanism for bridging the paper-digital gap envisions paper as a touch-sensitive device, predefining areas on a paper entity to be linked to different digital functionalities. The ergonomic characteristics of paper are preserved, yielding a thinner, more lightweight, and more flexible touch-sensitive interface. Selecting a position within a predefined active region triggers the corresponding functionality. Paper is thereby transformed from a passive to an active interface. Signer and Norrie's PaperPoint system is one example that uses this mechanism to bridge the paper-digital gap [69]. PaperPoint enables users to control presentations from a paper interface. In PaperPoint, interactive areas are defined on printed widgets, like buttons [69]. Functionalities linked to interactive areas correspond to what the button labels describe. For instance, when the "Show" button is selected, a particular slide will be shown. The benefit of adopting the "Active Regions" mechanism is apparent: paper provides an alternative, potentially more intuitive interface for interacting with a digital application.

6.1.2 Capturing Written Information. This mechanism involves capturing user marks written or drawn on a paper entity. Writing or drawing is a ubiquitous interaction with paper, described as organic and natural [72, 79]. Capturing the user's written or drawn input eliminates the need to manually transfer contents to a digital device, as is often required when simultaneously working with paper and digital technologies [22]. In Mackay et al.'s work, this functionality made communication between users more efficient [49]. The digital capture of a user's written input can be shared instantly and additionally used to trigger digital functionalities. In Tsandilas et al.'s Musink system, written gestures can trigger OpenMusic software commands [77]. For example, the user can define a crescendo on the music score by drawing the mark on paper. The two clear benefits of this mechanism are enabling users to use natural pen-and-paper interactions to interface with digital technologies and increasing efficiency by reducing redundant work.

6.1.3 Capturing Spatial and Physical Properties. This mechanism builds on paper's inherent spatial and physical flexibility by tracking its shape, position, and orientation, and by digitally utilizing the captured properties. One example of this mechanism is Holman et al.'s PaperWindows system [28]. PaperWindows tracks and projects windows onto physical sheets of paper. PaperWindows enables actions on the projected windows to be triggered with physical manipulations (e.g., flipping). For example, scrolling is triggered by flipping a paper "window" horizontally. This mechanism enables digital technologies to exploit rich and familiar interactions with paper to manipulate the digital world.

6.2 Extending Paper's Output Capabilities

The second approach for bridging the paper-digital gap involves extending the quantity and variety of information that a paper interface can display. Prior works have approached this problem from three perspectives:

6.2.1 Visually. The visual output capabilities of paper can be extended in two dimensions: temporally and spatially. Paper is an inherently static output medium with no support for displaying dynamic contents (i.e. content that can change across time). Holman et al.'s PaperWindows system [28] and Song et al.'s PenLight system [70] enabled the display interface of paper to become dynamic, supporting content which was previously incompatible with the medium, such as video. In addition to supporting the display of new media, this mechanism supports easy reconfiguration of the content displayed. Klamka et al.'s IllumiPaper, for instance, enables the color changes in the paper content [36]. Furthermore, Hincapié-Ramos et al. leveraged transparent-display devices to display additional contextually-relevant information (e.g., enabling users to tap on paper figures to show an overlay with additional information) [26]. Whereas paper is naturally incapable of temporal changes, with a hybrid approach, this is something that becomes possible.

Paper is inherently a self-contained medium, meaning its contents are always restricted to its physical boundaries (i.e., spatially restricted). On a given paper entity, like a document, the volume of content that can be displayed is limited to the size and shape of the page. Li et al.'s HoloDoc system overcomes this restriction by extending the display space of paper documents with a digital overlay [42]. The content of paper entities can extend into its surroundings (i.e., beyond its spatial limitations). From the HoloDoc example, we see benefits of this mechanism in supporting information oriented tasks, namely enabling access to more information than was previously possible. Paper is additionally limited in dimensional display; 3D content cannot be viewed or manipulated in a true-to-life state by 2D paper rendering. Song et al.'s MouseLight system enables users to view a 3D rendering of a building on top of a flat architectural plan [71]. The user is not demanded to extrapolate 3D geometries from 2D plans, and can interact more richly and intuitively with multilevel designs.

6.2.2 Aurally. Paper does not naturally support the capture and replay of sound. Several works in our corpus recognized the potential of embedded audio in paper. For instance, TAP & PLAY couples sounds with predefined interactive regions on paper to support language activities [58]. Listen Reader makes reading more immersive by embedding audio into the reading experience [4]. The sound content in Listen Reader is coupled with aspects like page position and reader hand proximity to designated page regions [4]. The two forms of audio prioritized by our corpus are speech and music [2, 4, 19, 37, 58, 72, 77].

6.2.3 Via Physical Actuation. This is a more sparsely represented mechanism in our corpus, but nonetheless noteworthy. States in digital systems can be coupled with the physical state of paper entities. For instance, in Probst et al.'s system, sticky notes are augmented with motion to provide physical feedback. One potential benefit of adding physical instead of visual feedback is that subtle motion cues optimize the trade-off between "attracting attention"

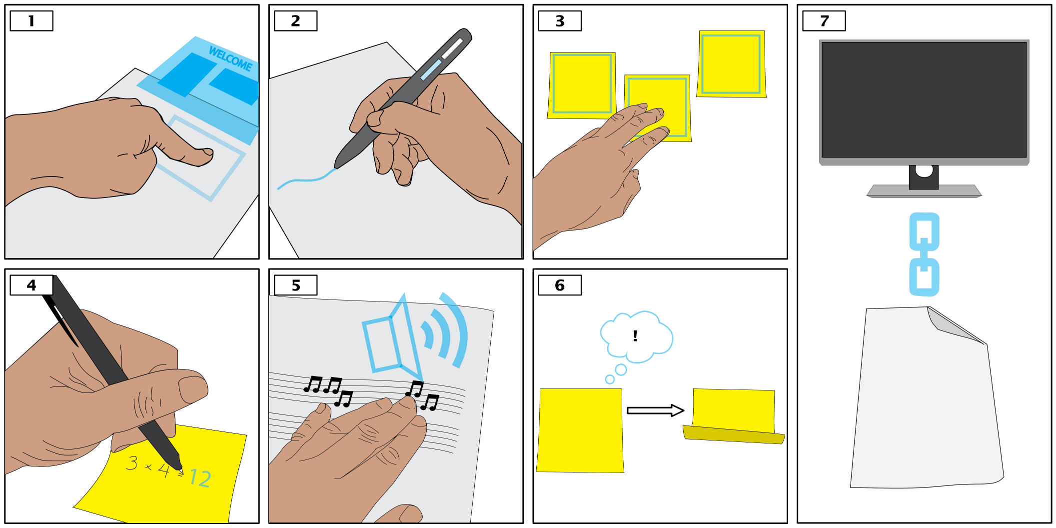

Figure 2: Approaches to bridging the paper-digital gap. (1) illustrates the concept of "active regions." The highlighted square in the diagram represents an area on the sheet of paper that is bound to some digital functionality, such as showing a virtual menu. (2) illustrates the input extension of capturing written information. The blue "ink" represents a mark that can be automatically used as input into a digital device. (3) illustrates the input extension of capturing spatial properties of paper entities. The blue highlights are meant to indicate that the position of the paper objects are tracked, as in Klemmer et al.'s work [39]. (4) illustrates a visual extension of the output capabilities of paper. This sketch draws inspiration from Klamka and Dachselt's work [36]. Here, we demonstrate a potential application of the extension in dynamically revealing answers for a learning application. (5) illustrates an aural extension of the output capabilities of paper. We show a potential application where touching a musical note could trigger the associated sound. (6) illustrates how the output capabilities of paper can be extended via physical actuation. Here, we demonstrate an application scenario where a paper entity is physically actuated to provide feedback in response to some predefined alert, as in Probst et al.'s work [60]. (7) illustrates the concept of enabling cross-media content associations.

and "reducing the negative effects of interruptions" [60]. This is desirable in certain contexts.

6.3 Enabling Cross-media Content Association

The last approach to bridging the paper-digital gap is enabling associations between paper entities and digital resources. This approach involves defining relationships between paper entities and specific digital resources, and then establishing methods for the two mediums to access one another. One example of an association is between paper interview transcripts and video recordings of the interviews [37]. To support oral history research, Klemmer et al. implemented a device to support fast access to video interviews from paper transcripts. While paper is easier to read, index, and navigate for researchers, it lacks video-recorded context of body language and tone of voice. Establishing cross-media content association enabled oral historians to access video recordings more conveniently. Another association was explored between physical medical records and digital medical records [29]. Houben et al. enable this association with their HyPR device [29]. This solution was developed to address the complications that arose as a result of the simultaneous usage of paper and electronic medical records. The association approach is particularly applicable in the "paper-digital coexistence" use case. When duplicate information exists in different formats, providing an association mechanism has the potential to streamline workflows.

6.4 New Affordances from Bridging the Paper-Digtial Gap

Bridging the paper-digital gap enables an extensive set of new and unique functionalities. In the following, we highlight three of the most salient features:

6.4.1 Greater Interactivity. By activating paper as an input device and extending its output capabilities, particularly to display content dynamically, the medium's interactivity is increased. Klamka et al.'s IllumiPaper method of enhancing paper, for example, enables the originally static interface to visually responsive to the user's interactions [36]. By integrating digital functionalities, paper can effectively be turned into a touch-screen device but retain its natural ergonomic qualities. Increasing paper's interactivity is one potential way of making interfaces for the digital world richer.

6.4.2 New Ways for Working with Information. The hybrid medium is able to support functionalities previously restricted to the digital realm. The works in our corpus took particular interest in enabling digital functionalities for organizing and navigating information, such as searching and indexing [10, 26, 42, 44, 45, 50, 70–73]. We expect the research priority of this set of functionalities to increase because growing information volume is one reason why paper-based practices are becoming unsustainable [23]. A hybrid approach enables retaining the desirable properties of paper, while also ensuring its use is compatible with modern needs.

6.4.3 Support for Remote Collaboration. Physical paper's incapability of supporting synchronous, remote interactions is a commonly addressed limitation in our corpus [17, 62, 70, 78]. User interactions with paper can be captured via previously discussed input mechanisms, then conveyed to remote users using the extended output mechanisms. Everitt et al.'s Distributed Designers' Outpost system supports remote, synchronous affinity diagramming by capturing the writing on and the physical placement of sticky notes, then displaying a virtual copy for the remote collaborator [17]. Previously, users were forced to choose between preferred paper practices and electronic communication mechanisms. This trade-off can be overcome by integrating both mediums into a hybrid interface.

6.5 Enabling Technologies

Among the most commonly used technologies for extending the input capabilities of paper are digital pens, such as Anoto and Livescribe products [22, 28, 69, 74, 83], and vision or motion capture technologies, like cameras, kinect sensors, Vicon systems etc. [28, 39, 52, 54, 73]. Both digital pens and vision or motion capture-based technologies are prone to sensing and recognition errors [19, 22, 39]. Digital pens provide high resolution written input capture [76]. The technology, however, restricts the user to pen-based interactions, as opposed to general touch interactions [14]. Furthermore, Anoto and Livescribe technologies require custom pen and paper. Vision or motion capture sensors, although affording more interaction flexibility, are limited by issues like restricted field of view and occlusion [7, 14]. Additional technological approaches to extend the input capabilities of paper include, but are not limited to, embedded electronics for sensing [18, 41, 85], touch-sensitive devices for input capture [49, 76], and custom-built devices [72, 83].

Visual extensions to the output capabilities of paper are implemented using either projections that present information directly on top of physical paper entities [15, 28, 54], mobile devices or transparent displays that employ a magic window metaphor and overlay additional content [12, 26, 73], head-mounted displays that supplement with virtual content [23, 42], or embedded electronics, like LEDs [36]. All methods of extending the visual output capabilities of paper suffer from issues of calibrating between virtual and physical space, limitations of field of view, problems arising from lighting variation, and occlusion [14, 23, 26, 49, 76]. Auditory extensions to the output capabilities are implemented by coupling paper interactions with external speakers. For instance, Anoto pen interactions with paper can trigger sound from the device itself [58]. To extend paper's output capabilities via physical actuation, works in our corpus relied on embedding electronics. The most illustrative example is Probst's Move-it sticky note prototype, which actuates sticky notes with shape memory alloys [60].

Cross-media associations are implemented through an embedded identifier on paper entities. Common identification methods we see across our corpus are the use of bar-codes [37, 53], RFID [29], and fiducial markers [73]. Overall, we can divide cross-media associating technology into sensor-based and vision-based groups. The limitations of vision-based extensions have been previously described. Sensor-based approaches require additional embedded hardware, which renders the original paper medium less accessible.

6.6 Discussion

Mechanisms for enabling direct access and control of digital resources using paper entities and extending paper's output capabilities ultimately represent building blocks for hybrid paper-digital interface solutions. For example, a common issue with paper-based practices is that they are neither "scalable" to manage high data volumes nor "up-to-date" [23]. Transforming paper into an interactive interface with easy access to digital functionalities represents a potential solution to this issue. Streamlining the link between the paper and digital world can eliminate the bottleneck that arises from paper and digital tools existing in parallel. By automatically digitizing interactions like writing on paper, users can forgo the time-consuming manual transformation process between the two mediums.

It is important to highlight that extending the input and output capabilities of paper are not mutually exclusive. Often, as part of a hybrid paper-digital system, paper is activated simultaneously as an input and output interface.

We identify several under-explored avenues for bridging the paper-digital gap. First and foremost, although this is currently poorly represented in our corpus, we see potential in further exploring the use of physical actuation to close the paper-digital gap. For instance, exploration of the use of motion to provide tactile feedback, in addition to providing purely visual attention, is missing from our corpus. Likewise, the use of paper manipulations as an indicator of intent (e.g., folding the corner of a book page as a bookmark or flipping to the back of a paper to hide information) offer rich potential as interaction mediums. We consider the potential of bringing these analogies into hybrid interfaces by enabling paper to achieve these motions autonomously. We also encourage researchers to experiment with newer augmented reality technologies. We see from the potential of augmented reality technologies, like the Microsoft HoloLens, in creating high fidelity hybrid paper-digital interface prototypes [42, 73].

Of course, we need to consider more than just the capabilities of current technologies in implementing hybrid paper-digital interfaces. In the following, we highlight the design considerations involved in determining use cases and enabling technologies.

7 DESIGN CONSIDERATIONS

Here, we highlight five design considerations pertinent to hybrid paper-digital interfaces. We acknowledge that additional considerations exist, and invite readers to examine our analysis, which we have open sourced. The points presented in this section are observed to be the most salient.

7.1 Possible Determinants of a Sweet Spot on the Paper/Virtual Spectrum

At a high level, we conceptualize each hybrid paper-digital system as a point on a paper-digital spectrum [39] to denote its composition of the affordances of the two mediums. Our first two design considerations relate to determining a "sweet spot" on the paper/digital spectrum, where the trade-offs between the aspects of paper and digital are optimized for a given usage scenario [39]. They are (1) physical experience replication and (2) digital presence.

7.1.1 Physical Experience Replication. To what degree do physical paper-based practices and experiences need to be replicated?

Gupta et al. argue that the extent to which physical experiences and operations need to be reproduced in a hybrid paper-digital interface depends on whether there is an analogue in the physical reality for a given functionality [23]. If a physical analogue exists for a given interaction, such as swapping photos in Gupta et al.'s application, then it should be replicated where possible [23]. This allows exploitation of the user's familiarity with an interaction. Additionally, as Gupta et al. have found, when replicating physical analogues where available generally increases user satisfaction [23]. Giraudeau et al. similarly advocate the advantage of hybrid interfaces in their ability to copy real interactions, but present a caveat [20]. They found that copying physical interactions could result in cases where the interactions are "too straightforward," and cause users to forget that the operations are in fact virtual [20]. As a result, users could unintentionally trigger unstable or even impossible states within the system that disturb their sense of immersion [20]. We regard this limitation as arising from the lack of maturity of current technologies in supporting desired interactions [20].

Designing appropriate interactions for cases where analogues do not exist is an open problem [47, 79]. For example, in Weibel et al.'s system, desired features (e.g., undo, redo, cancel) are impossible to organically implement in physical design space [79]. One solution is considering new modalities [23]. Gupta et al. recommend considering whether the new modalities require context switches or interfere with the physical experience [23].

Ultimately, we recommend preserving operations and experiences analogous to the physical counterparts wherever appropriate. As pointed out by Frohlich et al., users will always come to paper entities with expectations about their provenance, meaning, and affordances, inherited from their prior experiences [18]. Additionally, due to paper's ubiquitous status, it is embedded in the workflows and mental models of various tasks [49]. Hybrid paper-digital interfaces can benefit from respecting the roles of paper in existing practices where possible. As an example, since the interaction of writing or sketching on paper is heavily embedded in contexts like illustration, design, and note-taking, past works (e.g., [13, 72, 76, 78, 79]) on supporting these tasks preserved this interaction in their design. In a similar manner, for conventional paper-based practices which are inherently mobile, like note-taking for biology field research, the design of the hybrid paper-digital alternative should recreate the mobile nature of the task experience [83].

7.1.2 Digital Presence. To what degree are users comfortable with the presence of a digital component in the task under investigation?

In certain application domains, people are accustomed to practice with physical papers and find it effective for interpretation and input [73]. In such cases, people may be resistant to accepting digital features deemed to be an interruption of their physical rituals [15]. As discussed by Subramonyam et al., in the context of affinity diagramming, it is simultaneously difficult and essential to effectively leverage the digital component as a "background" role while actively supporting the task at hand [73]. In the context of affinity diagramming for design, constant digital intervention providing useful quantitative insights might be perceived by users as disruptive [39]. Minimizing the presence of the digital component may additionally be helpful in cases where users are not technologically literate, as put forward in Piper et al.'s work [58]. Ultimately, the appropriate invasiveness of a digital presence is a question that must be considered on a case-by-case basis. For Probst et al., since the use case is for non-confrontational peripheral display, digital presence is minimized [60]. For Holman et al., since the purpose is enabling paper's use as a flexible multi-window GUI interface, a high digital presence is acceptable [28].

Understanding user requirements for replicating physical paper experiences and user feelings towards a digital presence are important design considerations, particularly pertaining to ensuring that the paper and digital components of the system are appropriately balanced. We see achieving the so-called "sweet spot" on the paper-digital spectrum as a key design challenge for such hybrid interfaces.

7.2 Customizability

To what degree do users' approaches to a given task where there is potential for introducing a hybrid paper-digital interface differ depending on the individual? What kind of functionalities must be included to meet the users' personalized needs?

As we have previously highlighted, one key aspect of paper is its support for expressive, freeform capture and representation of information. Many works in our corpus leverage this affordance to develop interfaces for tasks involving highly personalized workflows and interactions. One example is in music composition, where composers tend to create their own ad hoc schemes for expressing ideas [19]. Strategies for note-taking, which involves imposing arbitrary structures for organization or using abstract marks as tools for triggering memory, likewise vary from person to person [78]. One common method of making interfaces customizable is enabling users to assign digital operations to written input [77]. Other works in our corpus exploit the versatility of paper as a medium for enabling users to create personalized interfaces for any given task [7, 34]. Becker et al.'s Tailored Controls system enables users to cut out their own custom GUI from paper [7]. The necessity of customization in the designs and interactions of a hybrid paper-digital interface depends on the task of interest. Tabard et al. argued that in the context of note-taking, interfaces should avoid restraining how users input information or decide on what users should capture [74]. Any system involving drawing or sketching in our corpus has maximized the users' flexibility [79]. Music-oriented interfaces use the aforementioned approach of enabling users to define their own written gestures [19, 77].

7.3 Support for Collaboration

To what degree is the system optimized for collaborative use? What sorts of interaction designs would be conducive to collaborative tasks?

Several works in our corpus target collaborative tasks. The positioning of these tasks on the computer-supported collaborative work (CSCW) matrix (e.g., synchronous versus asynchronous, remote versus colocated) has implications for designing a hybrid interface. In supporting remote interactions, a highlighted problem is identifying effective mechanisms to support rapport-building among users [17, 62, 79]. One approach, as adopted by Everitt et al., involves providing visual feedback to build a distributed sense of presence [17]. Visual feedback design remains an open question involving factors including but not limited to intrusiveness and handling physical-digital misalignments. Weibel et al. have noted that users also have the capacity of coming up with strategies to cope with the lack of feedback in a joint task [79]. In the context of remote collaborative sketching, one observed strategy to address the lack of feedback was agreeing upon spatial constraints in the shared sketching interface, so users do not sketch over each other [79]. The extent to which users can be entrusted with compensating for physical-digital alignment error is left to the judgment of the designer.

Past works have considered the functionality of replicating physical experiences in single-user contexts. How the practicality and desirability of replicating physical experiences upholds in less clear [23]. For instance, multiple users can impose spatial constraints in a shared physical area, rendering replication difficult. One additional point worth considering is the concept of private versus public experiences in collocated settings. This factor is discussed in Haller et al.'s work [25]. Their system uses paper interfaces as a private drawing interface, and provides functionality of sharing with the group via a large digital sketching wall [25]. Another approach to enabling collaboration with hybrid paper-digital interfaces, also discussed by Haller et al., allows the integration of paper with multiple devices [25]. The idea of providing a link between paper, displays, and data so multiple users can work both collaboratively and independently was also explored by Lange et al. [40]. It was shown to benefit collective tasks by making the team environment more immersive and connected.

7.4 Cost and Accessibility

Are there any limitations, constraints, or special needs on the users end that the design of the hybrid paper-digital interface must take account of?

As with the design of any interface, considering the financial constraints, (digital) literacy, access to technology, and special needs of end users is imperative. In resource-constrained environments, such as the domain targeted in Pearson et al.'s work, paper's affordability and availability was a key reason it represents a lucrative medium to couple with technology [57]. On the other hand, low-tech, easily accessible equipment such as non- or low-end smartphones component may constitute more realistic solutions to support access to information in resource-restricted contexts [57].We are surprised that work exploiting the affordability and availability of paper is currently limited, particularly in scenarios like the one addressed by Pearson et al. [57]. We consider this field of exploration worth considering in greater depth. Returning to the idea of digital presence, system design goals may prioritize abstracting the complexities of using a computer interface in scenarios of low technical literacy [58]. For demographics such as children or the elderly, emphasizing more intuitive paper interactions might have benefits over elaborate digital design [2, 58, 62].

8 DISCUSSION, LIMITATIONS, AND FUTURE WORK

The work presented here offers a synthesis of the key themes and trends in hybrid paper-digital interface research, which has thus far been lacking. In the following, we outline our recommendations for potential research directions and reflect on the limitations of our approach.

We currently see immediate opportunities in exploring more HMD and mobile augmented reality approaches. New technologies, like the Microsoft HoloLens, may provide an avenue for embedding digital functionalities into paper entities. Li et al. and Gupta et al.'s works form illustrative examples of the potential of using novel technologies as such [23, 42]. Based on this literature review, we additionally encourage researchers to explore the following:

- Designing appropriate feedback for paper-digital interfaces
- Designing interactions where physical analogues do not exist
- Managing current technological limitations, particularly misalignments between physical and digital, either through technical contributions or interface design research
- Further exploiting paper's characteristic as a highly affordable and available medium

Our ambition is that this work can be of help to future HCI researchers interested in the development of hybrid paper-digital interfaces. However, we should note that our literature review is not without limitations. We believe it is worthwhile to reflect on its potential shortcomings and indicate directions for future research.

First, we currently only focus on HCI-related venues. Considering our expectation that the next generation of hybrid paper-digital interfaces will be implemented using novel HMD and mobile augmented reality technologies, we recognize that venues like IEEE VR, VRST, and SIGGRAPH may offer a body of knowledge that usefully extends the work in our corpus. Our current corpus nonetheless contains a nontrivial number of works that use HMD or mobile augmented reality approaches. The works also beneficially provide a more human-centered understanding, which may be more appropriate and insightful to our target audience of HCI researchers. Finally, preliminary key-word searches into the aforementioned venues do not reveal substantial results. We acknowledge that there is still ample opportunity for future research, but regard our current work as a sufficient starting point.

Additionally, our review focuses on the motivations, implementation approaches, and findings of systems research papers. As we have acknowledged previously, this methodological decision was driven by our interest in actionable knowledge for developing hybrid paper-digital interfaces. This comes at the expense of knowledge from works which are more study-oriented, which we acknowledge as significant to the overall field. This literature review has revealed insights which may be informative to future designs. An intended future step is consolidating the findings from systems research (the results of our current review) to user study oriented work.

9 CONCLUSION

We contribute a consolidated understanding of the past thirty years of research on hybrid paper-digital interfaces. From our systematic literature review based on a sample of 60 papers from 13 HCI-related venues, we outline the relationship between paper and digital devices and the state of the art for our targeted innovations. We additionally discuss salient use cases, implementation approaches, and design considerations. As we move towards a future of ubiquitous computing, and as technologies enable digital functionalities to be more seamlessly integrated into everyday environments and objects, we expect interest in exploring paper as a potential medium for bridging the physical and digital worlds to persist. It is our hope that our work will provide a starting point to both inspire and inform this future.

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