Physical and Digital Media Usage Patterns on Interactive Tabletop Surfaces

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ABSTRACT
Concurrent interaction with physical and digital media is ubiquitous in knowledge work. Although tabletop systems increasingly support activities involving both physical and digital media, patterns of use have not been systematically assessed. This paper contributes the results of a study of spatial usage patterns when physical and digital items are grouped and sorted on a tabletop work surface. In addition, analysis reveals a dual character of occlusion, involving both inconvenient and desirable aspects. We conclude with design implications for hybrid tabletop systems.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces.

General terms: Design, Human Factors

Keywords
Interactive surface, tabletop display, paper, physical media.

INTRODUCTION
The ways we interact with information continue to evolve along with device form factors, computing speed, and ubiquity of access to networked information. Digital information can be displayed on the surface of desks, tables, or walls and can be manipulated using multitouch interfaces [41, 12] and tangible input devices [8, 34, 37]. Interactive surfaces are becoming common components of information-based activities [38, 11, 23]. Despite these changes and many other computing advances, use of paper in knowledge work, as elegantly documented by Sellen and Harper [31], remains pervasive. Paper provides key affordances not provided by current computers. For example, most users prefer reading printed documents to on-screen reading [1, 31]. As a consequence of this and other affordances of paper (e.g. ease of annotation and portability), paper is often involved concurrently with digital media. Similarly, while reading a printed document, users increasingly access digital information.

Because of ubiquity of its occurrence, we are particularly interested in use cases in which physical and digital media are both involved in an activity. A number of tabletop systems have been developed [38, 26, 16, 11, 7, 32, 13] that support such hybrid use but myriad interaction design challenges remain. Prior work has not, for example, systematically studied the affordances and tradeoffs involved in how users spatially arrange and group items or how they deal with occlusion of screen contents by physical items.

This paper documents users' spatial usage patterns while grouping and sorting physical and digital items on an interactive surface. It also investigates the impact of physical occlusion. The remainder of the paper is organized as follows: first, we discuss related work, next we describe the methodology and the main results, and finally we discuss key implications of our results for the design of hybrid tabletop user interfaces.

RELATED WORK
The present work is situated at the intersection of interactive surfaces [25, 6, 41] and tangible user interfaces [8, 14].

Affordances of digital and paper media
Empirical research [31] shows that paper provides key affordances for working with documents: it embodies and makes information tangible, supports easy bimanual navigation and organization, facilitates communication and collaboration, provides high resolution and high contrast for easy reading and a better viewing angle than horizontal displays [22], and enables intuitive annotation with a pen that is flexible and smoothly integrated with reading.

Multitouch interaction techniques on interactive displays are also designed to exploit direct physical manipulation [29, 33, 40]. A comprehensive study by Terrenghi et al. [33] compared the affordances of interacting with digital and physical media on tabletops. Analysis of basic tasks with photos revealed distinctive differences in the ways people interact with digital and physical photos. Most importantly, they noted that one-handed interaction predominated with digital media even though multitouch interaction is specially designed to support bimanual interactions. This might be partly explained by the lack of haptic feedback and by the restrictions of a two-dimensional surface. Piper and Hollan [24] compared the affordances of digital educational material on tabletops with traditional paper handouts in collaborative study practices. They found that the more

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ephemeral character of digital ink annotations encouraged students more than with paper to spontaneously create drawings to support discussion.

In contrast to studies that compare the affordances of physical vs. digital media, our focus is to understand the *combined* use of physical and digital media as a basis for designing hybrid interactive surfaces.

Hybrid interactive surfaces

Interactive desks, tabletops and walls enable users to manipulate physical and digital media on their surface [38, 26, 16, 11, 7, 32, 13]. The technical set-up typically consists of a top- or rear-projected display of digital information. Information from physical media can be captured with a camera or digital pen. In a number of systems, information can move between digital and physical environments [38, 11, 13]. Moreover, some systems allow users to create and follow hyperlinks between information contained on physical and digital media [26, 7, 32]. Prior work though has not systematically assessed the patterns of media interaction that emerge in hybrid physical-digital settings.

Managing space on the surface

Important and fundamental aspects of working on any surface are how the space is used and how information items can be arranged and manipulated. Scott et al. [30] performed an in-depth analysis of territoriality in collaborative tabletop workspaces. They found personal territories to be different from shared territories. Areas for storing items are integrated within these territories and change their positions over time. Other studies analyzed the impact of table size [27] and orientation of media [18].

Efficiently managing tabletop space and effectively assisting semantic organization commonly involves creating groups of items. Malone [20] in an early study examined how people organize papers on their physical desktops. Other studies [39] have examined how people manage paper archives and the tradeoffs involved between piling and filing. One consistent finding is that piling is a lightweight, casual activity, involving less overhead than filing. Concepts of piling on the desktop [21, 4, 2] and interactive tabletops [28, 3] have been presented. Examination of the literature reveals no studies of space management and grouping on hybrid interactive surfaces.

Physical occlusion of screen contents

Only a small number of studies have considered the problem of occlusions generated by physical objects on a display surface. Some work has dealt with occlusions generated by the user's hand and forearm when working with a pen on a tablet display [35]. Brandl et al. [5] proposed pie menus that automatically adapt their orientation to minimize occlusion created by the user's hands. Other work deals with occlusion generated by tangible objects [19]. It is important to note that all these approaches commonly consider occlusion solely as a bothersome phenomenon. As we describe below, a detailed analysis of occlusion shows that occlusion can also function to help users in expressing meaning.

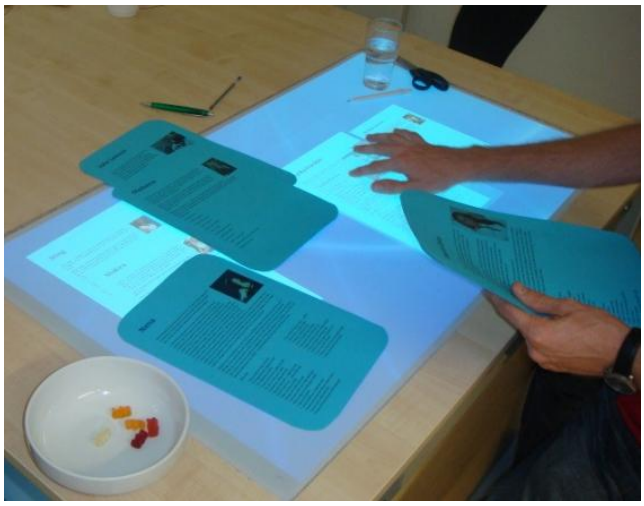

Figure 1. The study setting used a hybrid tabletop including physical and digital media.

METHOD

Participants

We recruited 10 volunteer participants (5 female, 5 male; 8 right-handers, 2 left-handers). All were experienced knowledge workers, from both technical and non-technical backgrounds (computer scientists, psychologists, jurists). All but 2 had little or no experience with tabletops. Their ages ranged from 24 to 46 years with an average of 32. No compensation was provided.

Technical Set-up

The study used an interactive tabletop of 130x105 cm size with a display size of 100x60 cm. This is representative of the space available on a typical desk. The rear-projection was full HD resolution (1920x1080 pixels). Rear-projection is currently the most common form of tabletop display. Moreover, in contrast to top projection, this ensures that our findings can be transferred to horizontal flat-panel displays. The participants were seated. They could interact with one digital document at a time using multitouch gestures for moving (1 finger drag), enlarging/shrinking (2 finger pinch gesture) and rotating (3 finger rotation). No physics simulation was applied. Printed documents could be placed and manipulated on the display surface and also on the surrounding non-display areas of the table. The setting is shown in Figure 1.

Materials

Participants were given 12 single-page documents. Each document contained textual biographical information about a popular musician. We used textual documents instead of photos (as used in other studies) for two reasons. First, working with documents is a more common and thus more representative knowledge work task. Second, since documents are typically larger than photos this increased opportunities for occlusion. To create a hybrid media setting, six of the documents were printed on paper (A4 size) and the

remaining six were displayed on the tabletop display. In a typical work setting, users might more commonly not have a common set of information items arrayed across digital and physical media but rather different types of items in each (e.g., paper articles or notes used while consulting web information). The motivation for splitting the set of documents between paper and digital sets was to simplify analysis. We also wanted to ensure adequate space was available for various arrangements. In each task, physical documents and digital documents were initially presented as two separate adjacent piles positioned at the center of the tabletop. All participants used the same set of documents.

Procedure

Each user participated in a single-user session of 40 minutes average length (SD = 8 min.). The specific tasks we asked participants to perform are common in knowledge work with printed and digital documents: a *grouping task* (inspired by [33]), a *sorting task*, and a *search and comparison task*. These tasks enabled observation of component activities such as selecting, reading, comparing, and moving items.

First, gestures for interaction with digital documents (move, enlarge/shrink, rotate) were demonstrated and participants became familiar with them. They then performed the *grouping task* and were asked to browse the documents and create three groups: those describing artists they like, don't like, or are unsure about. A *sorting task* followed in which they sorted all documents in a linear order according to a fact indicated in the document text, e.g the date of birth of the artists or their respective numbers of albums. The final *search and comparison task* required finding all albums which were released in the same year as one specific album by one artist. Therefore, participants had to compare all documents with one specific paper document and note down the names of the albums.

The *grouping* and *sorting tasks* were each performed first using only the paper documents, then only the digital documents, and finally with both document types. To help compensate for learning effects, different criteria for grouping and sorting were used in each iteration. The *search and comparison task* was directly performed with both document types. While performing the tasks, subjects were asked to think aloud and after each task semi-structured interviews were conducted. All sessions were videotaped using a camera mounted above the table and field notes were recorded.

Data Analysis

We coded 6.75 hours of video recordings for relevant behavior, iteratively refining the coding scheme. This led to the set of categories used below to describe behavioral patterns. Using the resulting scheme, we coded each instance of selecting an item, grouping and sorting items, and zooming and moving items. We also coded the duration and spatial placement patterns as participants worked with items. The resulting data supports not only qualitative analyses but also allowed us to derive statistical patterns. In describing these patterns below, we augment them in some instances with statements made in the interviews. While our primary analysis focuses on hybrid use, i.e. combined use of printed and digital documents, we also contrast this with patterns found in tasks that involved using only physical or only digital media.

RESULTS

We first describe the affordances of the combined use of physical and digital media. This includes the general spatial patterns of hybrid use and patterns of sorting and grouping. We moreover detail users' patterns of interacting with items and provide an analysis of how physical occlusion affects hybrid use.

Spatial Patterns of Hybrid Use

We are especially interested in how tabletop space is used in a hybrid setting. Initial analysis of the video recordings showed that participants distinguished between territories for working with (e.g., reading, comparing) and for storing items. As also reported by [30], the boundaries between these areas were quite flexible. We coded usage locations for each participant and aggregated this data. Figure 2 shows this aggregated data for the hybrid search and comparison task. Darker locations depict areas that were used by more participants. The wooden frame of the table is indicated by a gray border that encloses the white display area. The dark gray circle indicates the position of the user.

Figure 2 (upper part) shows the areas used for working with items. Note that physical and digital items tend to be used at different tabletop locations (graphically summarized in Figure 2 a and b). Physical items were used nearer to the user and more commonly to the left of the user. At times they were not directly on top of the display but on the edge of the table or even partially jutting off the table surface. In contrast, digital items were more tightly clumped, primarily positioned to the right and further away from the user than physical items. Note also that the working area for physical items involved a larger portion of the table, while the area for digital items was almost exclusively confined to the right of the table display. A reason might be that the haptic feedback of physical documents affords cognitive offloading, whereas the direct-touch manipulation of digital media requires visual attention. This fact could explain why the participants delegated macrometric tasks to the non-dominant hand, and micrometric ones to the dominant hand [10].

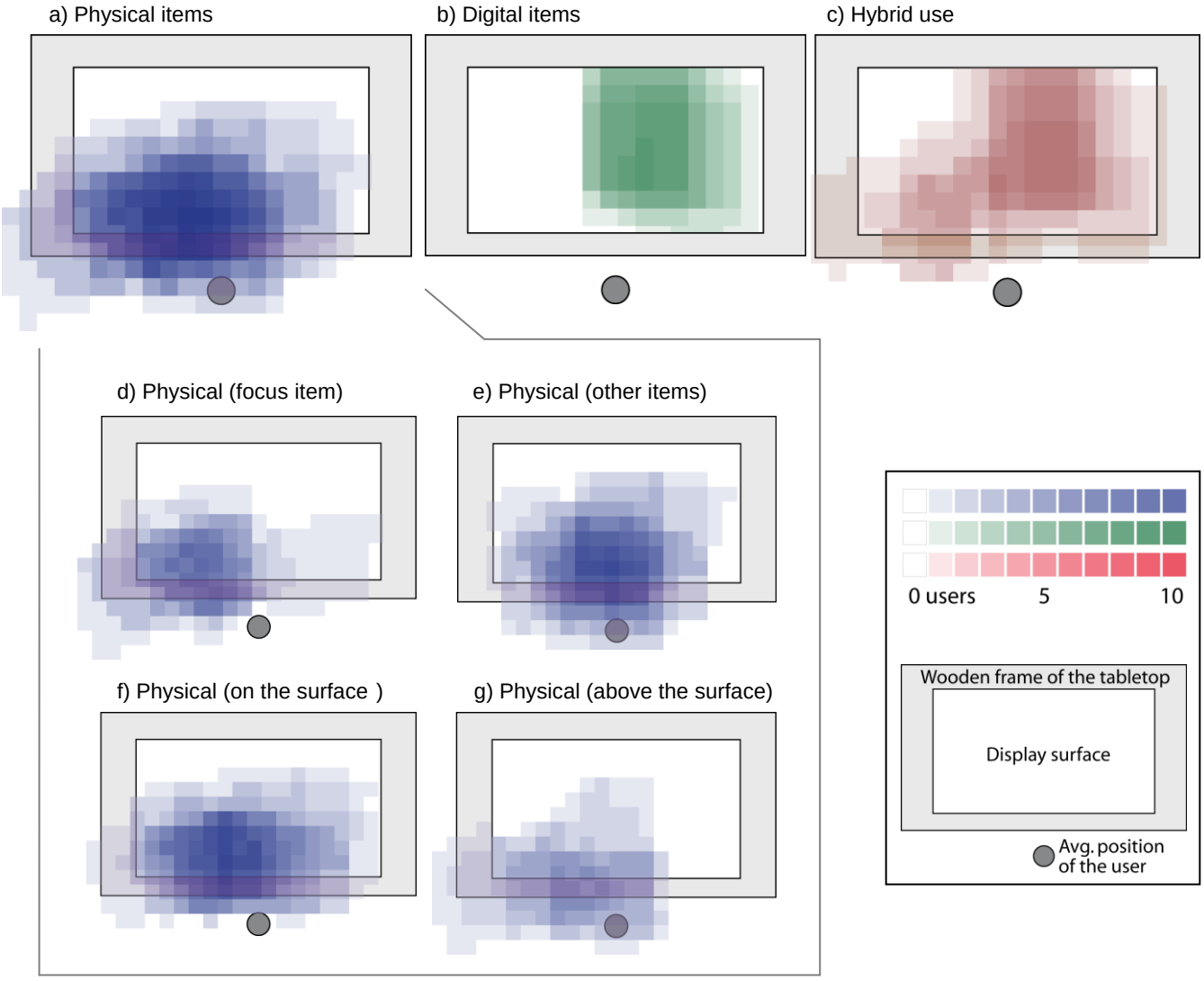

Figure 2. Activity maps depict areas where items were used on the hybrid surface in the hybrid search and comparison task. Darker areas signify use by more participants.

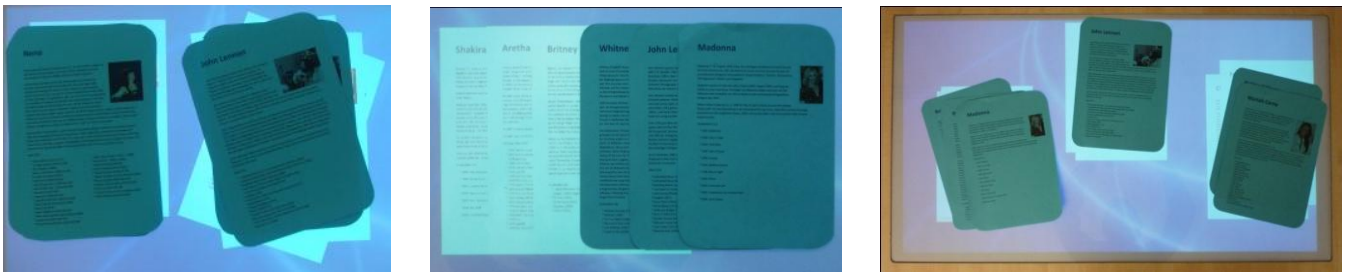

Figure 3. Examples of hybrid piles on the tabletop. Left: Neat pile and messy pile. Center: Spread-out representation, which affords getting an overview and comparing pages. Right: Result of grouping task created by one participant.

Figure 2 (lower part) depicts the areas used for storing items (i.e. locations of temporarily placed items for later use and of final placements). While the working areas were centered more in the middle of the table, storage is situated towards the outer left and right edges. Also, unlike working areas, storage area placement patterns are similar across physical, digital, and hybrid use. Note the clear difference in use of the tabletop area between storage and working, especially for physical and digital items. Again placement of physical items extends beyond the table surface. It is also important to notice that in contrast to working areas, physical and digital storage areas were co-located, with placement of physical and digital items overlapping.

In addition to working and storage areas, we found a third zone. In the search and comparison task one physical item had to be compared with all other items. Figure 2 d) shows that this item was used in a distinctive area, one differing from the other physical items involved in the task.

Figure 2 f) and g) show that physical items were not only used on the surface of the table but that there was also significant manipulation of these paper items above the table. We classified usage as being above-the-table if participants held a physical item (or collection of physical items) above the table for a period of time longer than was required to pick it up and directly placing it elsewhere. The illustration further shows that items in the air were held nearer the user and more to the left than physical items on the table surface.

Interacting with Items

Physical Items. Terrenghi et al. [33] compared how users interact with physical and digital media. They found that users tend to pick up physical items to bring them closer to their eyes. While their study did not involve piles, we observed that users manipulated individual physical items as well as piles of multiple items. When participants wanted to interact with an element, in the vast majority of cases they first selected a pile (45 cases) or an individual item (256 cases) by picking it up for holding it in their hands above the table. Only then they engaged in further interactions, such as reading or comparing information. Much less frequently, participants did not pick up the item and interacted directly on the surface with the pile (8 cases) or the individual item (20 cases).

The time span during which items were held in the hands above the table varied considerably. Sometimes an item was picked up, read and directly placed back on the table. But in most cases, the participants kept items in their hands for longer periods. In the grouping and sorting tasks, for example, most participants initiated the task by picking up all physical items and kept holding them while sequentially placing one item after another on the table to create an arrangement. Similarly in the search and comparison task, 7 of the 10 participants held the item to be compared continuously while comparing it with the other physical items placed on the table.

Digital Items. When interacting with digital items, participants in almost all cases enlarged the item using the zooming pinch gesture. In order to display the text in a readable size, digital documents needed to be enlarged, even though the resolution of our tabletop was higher (50 dpi) than that of most current tabletops. Enlarging was accomplished at the initial place of the document; only 2 participants (14 instances) dragged digital items from their initial position to a place nearer to themselves before enlarging, and only rarely did they lean their whole body over the table.

Hybrid Interaction. Simultaneously interacting both with physical and with digital items occurred in the search and comparison task. Participants in this task had to compare information contained on a physical item with information from all other items. While all participants interacted with digital items by enlarging them, strategies with physical documents varied. Three participants permanently held the paper item above the surface with the non-dominant hand. Seven participants placed the physical item onto the table surface near the digital items. This contrasts with how participants compared only physical items, where the majority held items in the air above the surface.

Hybrid Grouping

Unordered Group

We analyzed how participants interacted with groups that contain both physical and digital items. We were particularly interested in whether users prefer representing a hybrid group as two separate, possibly adjacent groups, each containing only physical or only digital media (spatially-separated representation), or if they prefer arrangements

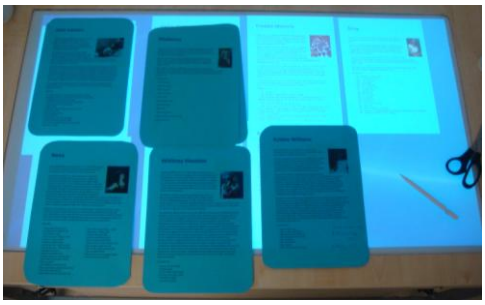

Figure 4. Representation of one single hybrid group in a sorted arrangement.

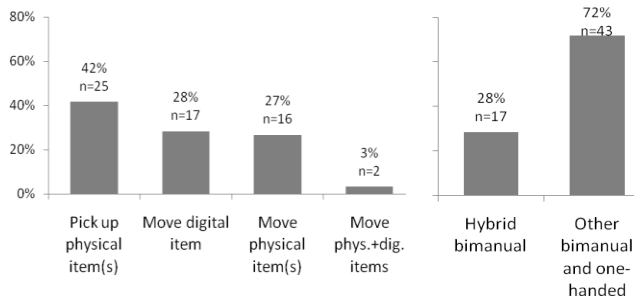

Figure 5. Strategies used for selecting occluded digital items.

that integrate both types of items at the same place (spatially-integrated representation).

All participants grouped physical and digital items in a single spatially-integrated representation, a layered arrangement that we call a *hybrid pile*. This is an arrangement of (largely or entirely) overlapping physical and digital documents. Figure 3 (right) shows an example of three hybrid piles created by one participant in the grouping task.

The spatially-integrated hybrid representation enabled participants to express a close relationship between physical and digital documents. Comments during interviews also underscored that participants preferred this spatially-integrated hybrid representation to other representations. For example, participant 9 explicitly mentioned that "having all [digital and physical items] in a pile makes sense". Participant 3 stated "I don't want digital documents to be [automatically] slid out" when placing physical documents on them. Due to the high degree of spatial proximity of overlapping physical and digital media, the overall gestalt [17] of a hybrid pile clearly expresses that the elements of the group belong to one conceptual group.

The creation and sequential browsing of hybrid piles appeared easy, fluid and dynamic. All but one participant created hybrid piles by first placing digital items on top of each other and then placing physical items on top of the digital items. To browse hybrid piles, all participants sequentially picked up the topmost item of the pile or dragged it away, starting with the physical before going on to the digital items.

Hybrid piles are more static than physical piles. Pure physical piles were frequently moved, whereas we observed no instance of an entire hybrid pile being moved. In addition, we observed frequent transformations of physical piles. Different pile organizations simplified specific practices. Placing all items neatly on top of each other saves screen real estate and supports interacting with the group as a whole, e.g. for moving and storing. In contrast, spreading out the items affords looking at the contents of several documents in parallel, e.g. for getting an overview, comparing and sorting items. In the pure physical condition, we frequently observed participants performing these transitions with one quick and intuitive bimanual movement. In contrast, in the hybrid case, we observed only two instances of such transitions. Most likely this is due to the fact that each digital item of the pile had to be displaced individually to transform the arrangement.

Ordered Group

In the second task, the participants had to sort physical and digital documents. This allowed us to analyze spatial arrangements chosen for representing *ordered* hybrid groups. In contrast to unordered groups, sorted hybrid groups could not be represented with a single hybrid pile, as the sorting could require placing digital items on top of physical ones. Instead of using vertical piling, 9 participants represented the ordered sequence by a horizontal arrangement. The upper left corner of a document indicated its position in the sequence whereby each document was placed to the right of its predecessors. In contrast, 1 participant expressed the ordered sequence by a combination of several adjacent hybrid piles (Fig. 4). Each pile in itself was ordered. Each time a digital item would have to be placed onto a physical document, a new hybrid pile was created beneath or below the preceding pile.

All participants viewed the hybrid sorting task as complex and the result as unsatisfactory. Each approach has drawbacks. The horizontal arrangement leads to a high degree of occlusion, since the tabletop did not provide enough space for placing all documents besides each other without overlaps. Moreover, this arrangement does not aid rearrangements. Inserting a document or changing its position within the sequence typically required rearranging many documents or even reorganizing the entire structure. The other approach, using adjacent hybrid piles, provided even less flexibility for rearrangements. As a further drawback, this representation conflicted with a conceptualization of one single ordered group. The resulting gestalt of several adjacent piles indicates not one but several different groups.

Physical Occlusion

We have identified and described patterns of use in hybrid tabletop settings. This provides a frame of reference for discussing how occlusion influences the activities of selecting, zooming, moving, and grouping items.

Selecting Occluded Items

Occlusion was most salient in our data when users wanted to access a digital item partly or entirely occluded by physical items. In order to analyze strategies used for accessing digital items, we characterized each selection

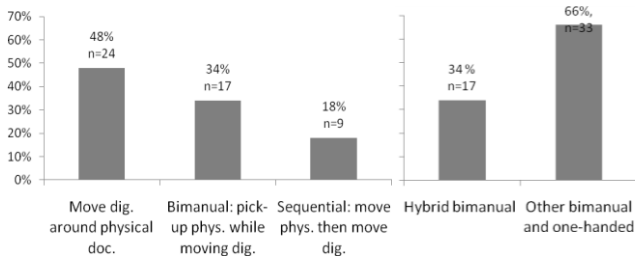

Figure 6. Strategies used for moving digital items over occluded positions.

activity from the video recordings. We noted the strategy used, characteristics of the occlusion (percentage of occlusion, number of occluding items and whether these items were part of a sorted arrangement), as well as features of the surrounding tabletop surface (percentage covered by physical and by digital items).

Figure 5 (left) depicts the four strategies we identified and their frequencies. The most frequent strategy (42%) was picking up the occluding physical item(s) so that the digital item became visible. A second strategy (28%) involved dragging the digital item to a non-occluded tabletop zone, the physical item resting untouched. Moving the occluding physical item(s) instead of the digital one was a third strategy (27%). A final strategy (3%) consisted of moving both the physical and the digital items concurrently to remove occlusion.

Participants leveraged the affordance of physical items to be moved not only on a flat surface but in all three dimensions. In addition, they performed a considerable number of bimanual hybrid interactions (28% of all instances). These involve manipulating physical items with one hand, while the other hand interacts with digital items. While we observed symmetric bimanual interactions, asymmetric interactions were more frequent. Participants typically picked up the physical item(s) with one hand (typically the non-dominant hand) and kept them in this hand while using the other hand to interact with the digital item (e.g. zooming). Finally, they placed the physical item(s) back onto the surface.

The selection of one of the aforementioned strategies highly depended on the degree of occlusion. If the amount of occlusion was higher, users tended to pick up the physical item(s), whereas in cases of less occlusion, users preferred to move physical or digital items on the surface. This correlation between degree of occlusion and picking up physical item(s) was highly significant ($r=.53$, $p < .001$, $N=60$). It was also highly significant for the degree to which the area *surrounding* the digital item is occluded by physical items ($r=.48$, $p < .001$, $N=60$).

We also analyzed how the selection affects the overall hybrid arrangement of items. Groups should remain groups and sorted sequences should not be altered by a selection activity. We observed that the overall arrangement of items remained the same before and after the selection if the digital item was occluded by only one item or by several unordered items. In these cases, the occluding items could be easily placed back in the correct arrangement after selection. In contrast, if the occlusion was generated by a higher number of items that by their arrangement expressed a sorting, it was much more complicated to place them back in the correct arrangement. In this case the structure was frequently destroyed by selecting the occluded item.

Zooming

As mentioned above, participants frequently enlarged digital items in order to read the contents. If one or more physical items are close by, enlarging can lead to occlusion. We observed 23 instances of occlusion resulting from enlarging. On average 30% of the item's surface was occluded (SD = 15%), with a maximum occlusion of 70%.

Despite even considerable occlusion, participants did not find it to be problematic. Since the task (for grouping, sorting, comparing) required access to specific information that was contained at similar positions on each document, participants could perform the pinch gesture to enlarge the document where the information was assumed to be located. While the document was being enlarged, the outer portions of the document expanded and moved under any nearby physical items, but the position of interest remained at the same non-occluded location and could easily be read. If the task required skimming or reading the entire document, occlusion would be more problematic.

Enlarging items that were partially occluded at their outer edges resulted in a cluttered view. The physical arrangement did not clearly convey whether the occlusion was accidental or the items were purposely arranged in an overlapping manner to express a relationship. Perhaps to avoid this ambiguity, in 65% of all instances participants immediately scaled down the item once they had read the information. Often enlarging, reading and scaling were performed in one integrated interaction using a single continuous pinch gesture. It is certain that zooming will be a less frequent activity in future tabletops, which will offer a higher resolution. Nevertheless, enlarging a view or an individual element is an important activity with many types of documents and visualizations, independently of the resolution available.

Moving

Moving items is a core interaction for managing a workspace. However, when using touch interaction to drag a digital item, one cannot move it across positions occluded by physical items. We were interested in how users would deal with this situation.

Figure 6 (left) depicts the three different strategies we observed and their frequencies. The most frequent strategy (48%) consisted of moving the digital item around the physical item. If this move-around approach would be tedious or even impossible, participants frequently leveraged hybrid bimanual interaction. In order to remove any obstacles in the motion path, they picked up the physical item with the non-dominant hand, moved the digital item with the domi-

nant hand to its target position, and then placed the physical item back onto the table. This strategy was used not only when a single item created the occlusion but also when entire piles had to be picked up. A third strategy involved first moving the physical item on the surface to free the path before dragging the digital item to its target position.

Piling

Participants' interactions with hybrid piles demonstrate that they intentionally generate occlusion by placing physical media items on top of digital media items. This spatial organization serves to represent and highlight a meaningful relation between the elements of a pile and thus rather than being problematic provides a visible representation of a conceptual relationship. As a consequence, it seems appropriate to distinguish between semantically meaningful forms of occlusion and forms that do not express semantic meaning. Occlusion in a hybrid pile can be *semantically meaningful* (and desired by the user when creating the pile).

In addition to this positive semantic aspect of occlusion, problematic features were also evidenced. Once a hybrid pile was created, physical items often entirely covered the underlying digital items. As a consequence, there was no indication that there were digital items hidden under physical ones. In interviews, five participants reported this to be highly problematic. In order to indicate the presence of digital items, three participants slightly displaced the physical items of a hybrid pile so that the digital items remained visible.

DESIGN IMPLICATIONS AND GUIDELINES

Based on the above findings, we propose the following guidelines for designing hybrid tabletop systems.

Support physical item use above and around the surface

Physical items were used not only on top of the display surface but were frequently placed on the margins of the table (even jutting off the surface) as well as being frequently picked up and held in the air above the table. The physical interaction space is larger than the digital interaction space, extending in all three dimensions. As a consequence hybrid tabletop systems that plan to support use of physical items should track them not only on and directly above the surface but also on and above the table edges and even in front of the table. This is not possible in current tabletop systems that track tangibles with fiducial markers using a camera below the table. Tracking should cover areas beyond the tabletop; for example, our findings suggest areas in front of the display and to the side of the table associated with the user's non-dominant hand.

Support physical, digital and hybrid information groupings

Our study demonstrates once again that people can work very flexibly with collections of physical documents. Users easily interact with and move groups of physical items to accomplish tasks and manage workspace organization. Hybrid piles without better technological support lack the ease and the flexibility for moving and rearranging that traditional piles of paper documents afford. Therefore, it is particularly important that tabletop systems provide easy natural mechanisms for users to create groups of digital as well as hybrid items and enable interaction with them as single entities. Soap bubbles is one promising metaphor [36, 15].

For a sorted group of hybrid digital and physical items, however, a hybrid pile is not currently a very effective representation. Future work needs to identify new representations for hybrid piles and mechanisms of interaction. In particular, how users might easily transform items between physical and digital representations should be explored so the advantages of each representation might be exploited.

Support transitions between pile representations

We frequently observed that users transformed piles of physical items to another arrangement to assist the task being performed. For example, a "tidy" pile affords interaction with the group as whole, whereas a juxtapositioned or partially overlapping arrangement affords an overview of the items as well as reading or comparing them. With physical items, transformations were fluid and typically performed with one bimanual movement. Similarly fluid transitions between different representations should be supported for digital and hybrid groups. The digital members of a hybrid pile could, for example, automatically imitate arrangements that result from moving physical members [15].

If a hybrid pile is transformed to a spatially-separated representation (i.e. split into separate physical and digital parts), our results suggest placing the digital portion to the side associated with the user's dominant hand. This enables hybrid interactions using the non-dominant hand for manipulating physical items and the dominant hand for interacting with digital items.

Provide awareness on and support interaction with occluded digital items

In a hybrid setting, digital items can be occluded by physical items, losing any indication of their presence. Hybrid tabletop systems should indicate the presence of occluded items, for instance by displaying a halo around a physical item that fully occludes one or more digital items.

When new digital items are added by the computer they should be automatically displayed at a non-occluded position on the screen if possible. However, if the user occludes a digital item (e.g., by placing a physical item over it), it should *not* be automatically repositioned to a non-occluded area. Our findings show that frequently occlusion is desired by users and can be semantically meaningful.

Nevertheless, selecting occluded items should be made easier to accomplish. Interfaces should permit users to temporarily display occluded items (perhaps as the result of hovering) at non-occluded positions to enable easy selection. As another example, a digital handle could be displayed at the edge of a physical item to make it possible to easily pull out the occluded digital item. Once the handle is released, the digital item could automatically snap back to its original position. Further, hybrid tabletop systems should support moving digital items over occluded positions without the need to remove the occlusion.

Support occlusion-aware enlarging of digital items

The study has shown that due to the limited resolution of current tabletop systems, users frequently enlarge textual documents to be readable. If the surrounding area is occluded, enlarging can lead to partial or complete occlusions as well as to a cluttered arrangement. Perhaps because of this, in most cases users immediately scaled down the item after reading its contents. Hybrid tabletop systems should provide efficient support for interacting with digital items in occluded contexts. A zoom lens could provide help for easily and quickly focusing on parts of an item without causing the entire item to be enlarged and occluded. Fisheye views [9] or automatically mirroring an item to a non-occluded area in an enlarged view could also support access.

Limitations of the study

While most findings can be generalized to other cases of hybrid tabletops, some limitations apply due to the setting of the study. The initial presentation of documents as two adjacent piles might influenced the grouping patterns chosen by participants. While this bars us from deriving quantitative results, the study shows that the pattern of hybrid piles exists and that it can be efficiently integrated into work practice. This is inline with previous findings on piling [20, 21, 39]. As a second limitation, we assume that the findings related to zooming are influenced by the still rather low resolution of current tabletops. Future work should examine how users focus on digital documents on higher-resolution tabletops. Finally, the study only addressed rear-projection setups. We leave to future work to examine hybrid document usage in front-projection setups.

CONCLUSIONS

This paper contributes to understanding activities in which physical and digital media are both used on interactive tabletops. We explored the affordances and tradeoffs involved in how users spatially arrange and group items and how they deal with occlusion of screen contents by physical items. The results revealed a spatially integrated use of physical and digital items. While the areas for *working* with both types of media differed (in general, physical items were placed nearer the user than digital items and were less clumped), the same areas are used for *storing* items. In particular, participants frequently stored groups of items in a hybrid pile arrangement. Users are willing to physically occlude digital contents in order to better manage their workspace and to make meaningful collections. When coping with occlusion, participants had highly effective strategies that rely on bimanual interaction.

Based on the study results, we proposed design recommendations for future tabletop interfaces. The results highlight the need to support physical interaction not only on, but also above and around the surface. Moreover, future tabletop interfaces should enable the user to create and flexibly manipulate hybrid groups that include both physical and digital items. In addition, systems should appreciate the positive semantic aspects of occlusion as well as trying to confront the problems occlusion can engender. Finally, there is a need to support better access to occluded items and enable efficient interaction with them (e.g., in selection and moving). This is an important aspect of bridging the gap between the physical and the digital worlds.

We have explored a setting in which digital items could be moved and arranged on the tabletop much like physical items. In addition to suggestions enumerated above, future studies should also assess the effects of occlusion with tabletop interfaces in which digital media cannot be freely arranged, such as a large map or graph.

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