ObjecTop: Occlusion Awareness of Physical Objects on Interactive Tabletops

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ABSTRACT

In this paper, we address the challenges of occlusion created by physical objects on interactive tabletops. We contribute an integrated set of interaction techniques designed to cope with the physical occlusion problem as well as facilitate organizing objects in hybrid settings. These techniques are implemented in *ObjecTop*, a system to support tabletop display applications involving both physical and virtual objects. We compile design requirements for occlusion-aware tabletop systems and conduct the first in-depth user study comparing ObjecTop with conventional tabletop interfaces in search and layout tasks. The empirical results show that occlusion-aware techniques outperform the conventional tabletop interface. Furthermore, our findings indicate that physical properties of occluders dramatically influence which strategy users employ to cope with occlusion. We conclude with a set of design implications derived from the study.

Author Keywords

Interactive tabletop displays, occlusion awareness, hybrid physical-digital interaction, multitouch.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Interactive tabletop systems are becoming increasingly widespread, with researchers starting to investigate classroom [9] and even home [6] use. Ever decreasing hardware costs means we can anticipate that these systems will become part of daily life as desks, meeting tables or dinner tables with integrated displays. Due to their horizontal table-like character, it is likely that users will place everyday physical objects, such as papers, magazines, laptops, and coffee cups, on the display surface. This creates a hybrid physical-digital setting where both types of objects are manipulated on one surface. In contrast to digital interface elements that are part of a system's design, it is hard to anticipate where physical objects will be placed, how people will use them, and importantly the system cannot move or manipulate them if they occlude digital objects on the display.

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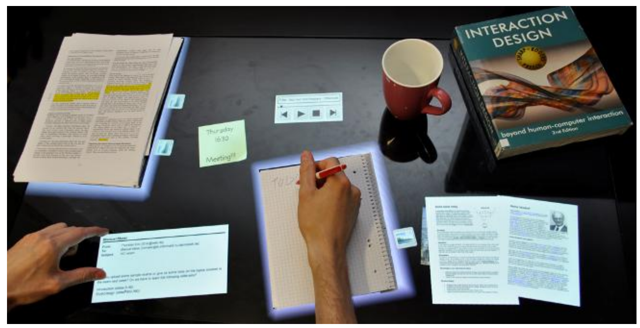

Figure 1. ObjecTop facilitates working on interactive tabletops in hybrid settings involving both physical and virtual objects.

Tangible interface elements on tabletops (or hybrid surfaces [22]) have been extensively studied [11, 3, 17]. In such interfaces, the tangible elements are themselves part of the system and tightly coupled to the digital elements on an interactive display. While these prior studies provided the first insights for hybrid digital tabletops we still lack an understanding of how to address the challenges emerging from concurrent use of *ordinary* physical objects in combination with digital objects on interactive surfaces. Successful integration of interactive surfaces into everyday life depends on addressing and providing practical solutions to these challenges. In this paper, we focus specifically on the challenge of physical occlusion. We argue that hybrid tabletop settings pose challenges for both *display* and *interaction*. Physical objects may hide or partially occlude digital items, create issues because users are unaware of the presence of occluded items, make access difficult, and restrict screen areas for display and interaction.

Work is emerging that addresses parts of this problem space: detecting [20] and avoiding occlusion [4,21], as well as providing support for staying aware of and accessing digital objects [5]. As such, this pioneering work established first design principles for specific points in the design space, which inspired our work.

Extending beyond previous work, this paper contributes the first system that supports all major occlusion-related activities by providing an integrated set of interaction techniques for not only access and awareness, but also interaction with digital objects throughout the tabletop surface and organization of the hybrid physical-digital space. All the techniques are designed following guidelines derived from an initial field study. They are coherently implemented in the *ObjecTop* system so that users can fluently interact and organize objects in a realistic hybrid tabletop setting.

The second main contribution of this paper is results from the first user study that formally evaluates interaction with occlusion-aware techniques on tabletops in situations that involve both physical and digital objects. Based on findings from this study, we propose a set of guidelines to inform design of practical solutions and interaction techniques for hybrid tabletop systems.

RELATED WORK

Occlusion by Physical Objects

The literature on occlusion created by physical objects on interactive surfaces is limited. Steimle et al. [10] conducted a study of patterns of combined use of physical and digital documents on interactive tabletop surfaces. The study identified several problematic aspects of occlusion, but also highlighted advantageous aspects of occlusion that at times can help users effectively manage and organize their workspace. This tradeoff can be complex for design. For example, when users *intentionally* occlude digital objects, e.g. when creating a pile, these objects should not be automatically relocated by the system. In such cases the authors suggest that the system should provide better awareness of and accessibility to occluded items.

Systems have been designed to mitigate problems of physical occlusion on tabletop displays. Javed et al. [5] presented six different techniques to address occlusion in a physical-virtual setting. Each of these techniques helps users deal with a single issue such as identifying or accessing occluded digital objects. The techniques are evaluated through two experiments in a simulated hybrid setting using virtual occluders, but no physical objects. Their results indicate that techniques that consume less space and provide less visual clutter are in general more promising. The study shed light on the characteristics of each individual technique and inspired the design of some of our techniques, such as the halo visualization. The goal of the SnapRail [4] system was to alleviate the problem of physical occlusion on tabletops by automatically rearranging digital objects on a rail around the occluder. Freeman et al. [20] present a technique to find uncovered areas on a tabletop surface to represent occluded content.

We extend these prior studies in three ways. First, ObjecTop presents an integrated interactive solution and techniques for hybrid tabletop settings that seamlessly supports awareness, access, and interaction with virtual objects as well as their organization. Second, we study these ObjecTop facilities in a true hybrid setting using everyday physical objects. This enables assessing the influence of physical properties of occluders on the strategies users employ to cope with occlusion. Third, we compare our techniques with the natural way of coping with occlusion of everyday physical objects: moving or lifting the occluder. To our knowledge, this is the first such study.

Other researchers have proposed approaches to occlusion-avoidance for hybrid tabletop settings. Cotting and Gross [21] describe a top-projection display metaphor that automatically projects freeform bubbles on free areas of a tabletop. Leithinger, Brandl et al. [7, 2] present a user-driven solution to draw on-the-fly menus of custom shape around areas that are occluded by physical objects. In contrast to this work, ObjecTop allows for occluding digital objects and at the same time provides occlusion-aware support.

Occlusion by the User's Hands

Our work also relates to prior studies focusing on occlusion of screen contents created by users' fingers, hands and forearms during direct touch or pen-based input [12, 13, 14, 15]. Shift [12] addressed the problem of finger occlusion on small handheld touch screen devices by displaying a callout showing a copy of the occluded screen area. Vogel et al. [14] presented a similar technique for stylus displays based on a detailed model of the user's hand. This model was later refined for multitouch gestures [15]. Occlusion by the hand and forearm is considerably different from occlusion by physical objects because physical objects are generally less frequently moved, have less predictable shapes, and can be more numerous as most of our desktops attest by the common presence of piles of papers, magazines, soda cans, coffee cups, and other objects.

Occlusion in Digital Settings

Occlusion of digital content is not a problem exclusive to hybrid tabletop systems. Overlapping windows in WIMP interfaces pose similar challenges. A variety of solutions have been presented, including taskbar widgets, semi-transparent windows [18], spreading out overlapping windows [19] and content-aware techniques [16]. These techniques are not applicable for physical occluders, since in contrast to screen contents, physical objects cannot be automatically relocated or made transparent.

REQUIREMENTS FOR OCCLUSION-AWARE TABLETOP SYSTEMS

In order to better understand requirements for supporting users in hybrid settings, we carried out an initial exploratory study. We were particularly interested in how users interact with a hybrid setting consisting not only of paper documents as in previous work [10] but also other everyday objects. The study involved single-user sessions (~1 hour) with 6 volunteer participants (1 female, mean age=28) recruited from a university department. All participants were familiar with interactive tabletops. In the study, we used a Samsung SUR40 tabletop running a Bing sample application, allowing users to search for images and geographical locations using the Bing Internet search engine. Query results included images and maps with which users could interact using common multitouch gestures.

Users were asked to organize a conference in the local city. This required participants to look for suitable hotels, a conference location, and a place for a social event. Participants were asked to physically document their results and draw a map of the locations using pen and paper along with presenting their visual search results. Participants were encouraged to bring and place their everyday objects such as cell phone, wallet or coffee cup on the display surface. An iPad was also provided in case users needed to textually search for further information about hotels or locations. Following completion of the task a semi-structured interview was conducted with each participant. Sessions were videotaped. The main findings and prior study results [10] suggest a set of requirements for occlusion aware tabletop systems.

R1) *Support the positive aspects of occlusion*. We frequently observed participants concealing digital objects for various purposes. For example, they did this to hide objects no longer being used following a focus or task switch, to reduce visual complexity of the workspace, or to group or pile a set of digital and physical objects. Participants (P2, P3, P5, P6) pointed out other situations in which they would want to deliberately hide an object, similarly to minimizing a window in a WIMP interface. Similar to the findings in [10], participants also mentioned that techniques such as automatic relocation of occluded objects that do not adequately take useful functions of occlusion into account might be troublesome and decrease the feeling of workspace control.

R2) *Support for occluded virtual objects*. Participants confirmed the importance of accessibility and awareness of occluded objects and emphasized that visual clutter should be minimized. P3 added *"having a mixed set of digital and physical objects overlapping one another does already [create] a lot of visual clutter, adding a heavy system support [visualization] can make it worse!"* This accords with the findings of [5] and their suggestion to provide lightweight awareness techniques for tabletop applications.

R3) *Support occlusion-aware workspace* management. Our observations and participants' feedback revealed that to support effective work in hybrid environments requires not only providing awareness of hidden digital objects but also facilitating organizing and structuring the entire workspace. P3 stated "*look! [the participant showed moving a digital object through several physical objects] moving this digital one in the hybrid setup is like playing a Maze game; this is suboptimal and tedious in contrast to the fast digital move gesture*." Ideally users should be able to relocate, pile and structure virtual objects as easily as when there are no physical objects present on the tabletop surface.

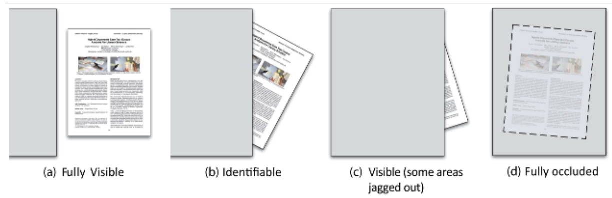

Figure 2. Occlusion Continuous Spectrum.

R4) *Occlusion is not binary*. We observed that occlusion occurs in varying degrees, ranging from full occlusion, with occluded objects not visible at all, to partial occlusion, to full visibility (cf. Fig. 2). In addition, partially occluded elements can be identifiable or unidentifiable and accessible for manipulation or not. Occlusion-aware tabletop systems need to provide appropriate levels of information about occluded objects and ways to manipulate them. In addition, how occluded objects are represented should be sensitive to context and user task.

R4) *Provide physical anchors*. Participants frequently expressed that in a hybrid setting physical objects are dominant. P2 said *"[physical] objects are graspable and always atop the digital items and this makes manipulation of them much easier."* Participants suggested explicit interactions such as linking and moving multiple virtual objects using a physical object.

INTERACTION TECHNIQUES

This section presents the ObjecTop interaction techniques through the design rationale we followed in order to meet the requirements outlined in the previous section.

Awareness and Accessibility of Occluded Items

Once occlusion takes place, ObjecTop implements an interactive halo representation (similar to the non-interactive Glow technique in [5]) to provide awareness of occluded items. The halo is visualized around the occluding physical object as illustrated in Fig. 3a. The occluded object remains in its original location (**R1**) but an icon-sized miniature representation of it is visualized on the halo. This indicates the rough spatial location of the occluded object relative to the occluding physical object and provides additional information about the occluded object.

In contrast to the non-interactive Glow and Icon techniques in [5], both the halo and the individual icons act as interactive widgets to preview and access occluded objects. Icons provide access to individual occluded objects (**R2**). In order to access all underlying objects users can also drag out and enlarge the halo (cf. Fig. 3a). The halo visualization enables global awareness of occluded objects as well as access to occlusion groups and individual objects, while

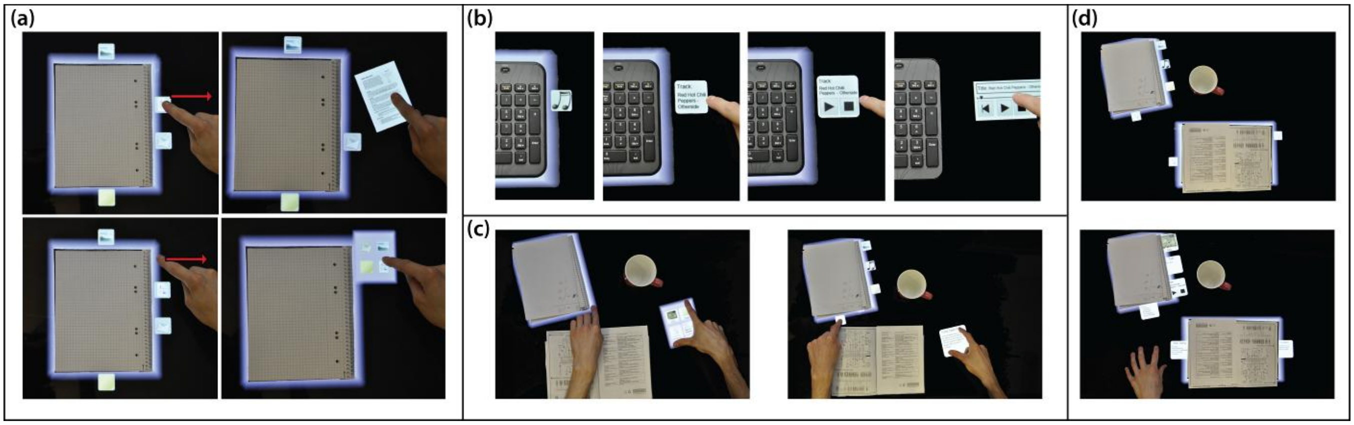

Figure 3. Support for awareness and accessibility: (a) interactive halo, (b) gradual access, (c) remote access, and (d) global exposé.

minimizing visual clutter. Displaying the basic halo and icon visualizations enables design of additional interaction techniques: gradual access, remote access, and global exposé.

Gradual Access

ObjecTop provides gradual access to occluded objects. While the user is dragging an individual icon or a group of occluded objects, interactive previews of increasing levels of detail are shown before eventually displaying the object itself in full detail (cf. Fig. 3b). Inspired by [5] and semantic zooming notions, four levels are supported (**R4**).

- *Presence:* provides presence information about an occluded item under the physical object. This includes the type, number and rough location of occluded objects. This level minimizes visual clutter, providing only an indication of the presence of occluded objects.

- *Identity:* shows the identity of the occluded objects by providing an icon and title.

- *Interactivity:* shows detailed preview information such as a thumbnail or miniature version of the occluded object. Similar to the thumbnail view on the Windows taskbar, it provides basic functions so that users can interact with an occluded object without retrieving it.

- *Full access:* the occluded object is detached from the halo and moved to a position outside the area of the occluder. If a user releases an object before it is moved to full access, the object automatically snaps back to the halo representation.

In previous work, each occlusion level is supported by one or more techniques individually. Those techniques which support presence or identification levels (Glow, Icon, Pile, Minimap [5]) do not support interactivity or access to the occluded objects. In contrast, other techniques (Move and Replicate [5]) enable full access to the occluded objects, by always moving them to non-occluded areas. As noted in previous work, this approach consumes a high amount of space and generates high visual clutter [5]. ObjecTop provides presence and identity while minimizing visual clutter and, at the same time, enables users to gradually access various levels of detail of occluded objects. Gradual access offers a lightweight way to peek at an occluded item or an entire occlusion group, at the desired level of detail.

Remote Access

If several physical objects cover a tabletop area, there might not be sufficient uncovered adjacent display space available for gradually accessing occluded items. We designed a bimanual gesture that enables users to access occluded objects on any empty spot on the tabletop surface (**R2**). While touching a halo or an individual icon with one hand, the other hand performs a pinch gesture on any other area of tabletop display as depicted in Fig 3c. The pinch gesture opens an interactive preview of the object or the occlusion group, offering the same functionality as the direct technique described above. By pinching the fingers apart, the preview gets larger and shows more detailed information. Once the preview is opened, the user can release the finger on the halo to interact with the preview or to reference to another halo. The preview disappears once the pinch gesture is released.

Global Exposé

In addition to supporting access to occlusion groups and individual occluded objects, ObjecTop offers a lightweight way to obtain an overview of *all* digital items on the tabletop (**R2**). The global expose mode is triggered by a five-finger gesture on an empty tabletop area (cf. Fig. 3d). It automatically moves and scales all occluded objects to become visible. The user can grab any digital object and move it to a new location. In order to avoid permanent clutter, upon releasing the fingers, objects that were not moved snap back to their original, occluded locations.

Organizing the Hybrid Physical-Digital Workspace

Organizing information and objects on the physical desktop is a semantically valuable and common activity for users [23]. ObjecTop supports frequent organizational activities such as moving or piling in hybrid tabletop settings by offering a set of bimanual techniques.

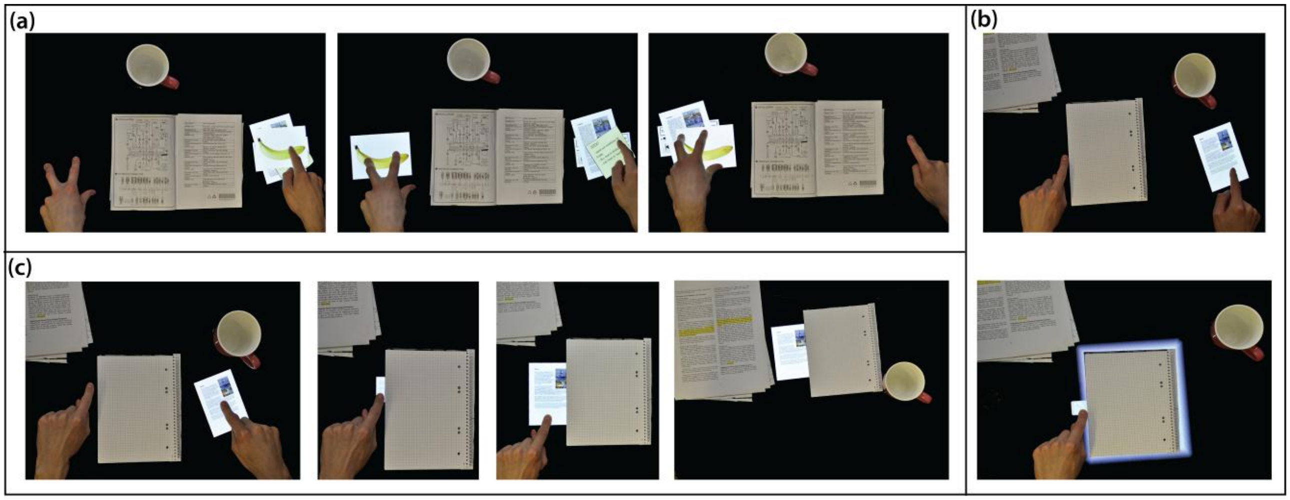

Figure 4. Gestures to support organizing digital objects: (a) teleport, (b) hybrid piling and hiding, (c) hybrid binding.

Moving across occluders

Moving is one of the most frequent activities when dealing with either physical or digital objects. In hybrid settings however, moving of digital objects can become challenging due to the presence of physical objects on tabletops. Physical objects may block the path across which a virtual object can be dragged. Users need either to move the physical object out of the away or move along a less direct path. We designed a bimanual moving technique called *teleport*. One hand indicates the destination with a tripod-like three-finger gesture and the other hand flicks the object towards the finger tripod (cf. Fig. 4a) (**R3**). In comparison with free flicking gestures, teleport is more precise by specifically indicating the destination. This is critical in hybrid settings, as otherwise flicked objects could end up covered by an occluder. In addition, it can be employed to quickly collect many digital objects in a pile, by flicking multiple digital objects from across the tabletop to the same destination.

Hybrid piling and hiding of objects

Another common workspace organizing activity is piling or stacking to create groups of physical and/or digital objects [10] or to reduce visual clutter by deliberately hiding objects underneath other objects. To support this activity, users can perform a simplified variant of the teleport gesture by placing one or two fingers on the halo (or close to the edge of the physical occluder) and performing a flicking gesture (cf. Fig. 4b) (**R3**). In this way users can create hybrid piles or deliberately hide one or multiple virtual objects underneath a physical one (**R1**).

Hybrid binding

People frequently bind or associate physical objects to one another, for instance by stapling multiple sheets of paper together or by sticking post-its notes onto documents. Binding indicates some relation between the attached objects and can enable easier access and comparison once objects are bound. We designed a bimanual gesture so that users can attach digital to physical objects (**R5**). To do so, the user touches the digital item to be bound and performs a swipe gesture along an edge of a physical object (cf. Fig 4c). The swipe gesture is inspired by the action performed to close a zipper. While swiping, users can adjust the size of the area used to dock the digital object to the physical one. Once attached the digital item automatically moves with the physical object when it is moved. To detach, users can simply drag off the docked digital object.

IMPLEMENTATION

We implemented the occlusion-aware techniques described above in a fully functional system (written in C#) running on a Samsung SUR40 tabletop system with screen resolution of 1920x1080. Fiducial tag markers enable tracking physical objects on the tabletop surface. Although this requires augmenting objects with tags in advance to recognize physical objects placed on the tabletop surface, it aids study of the occlusion aware techniques and avoids any additional top-mounted instrumentation.

The system detects percentage of occlusion. Specifically, when more than two-thirds of a digital object is covered, it is recorded as being occluded. Though practical for identifying many occlusion cases, this approach does not take the content of the object into account. Future work should explore use of object content as a factor in determining occlusion [16].

USER STUDY

With a conventional tabletop system, the usual strategy to cope with physical occlusion is to move and lift physical occluders [10]. One aim of our user study is to formally compare this well-established strategy with ObjecTop techniques for providing awareness and visibility of occluded items. The objective is to compare performance for a set of common tasks in both low and high cluttered hybrid tabletop conditions.

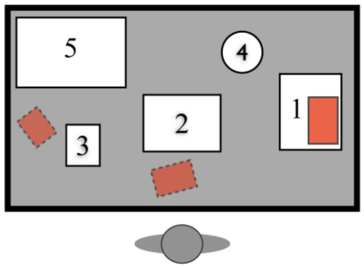

Figure 5. Initial Arrangement of Physical Objects in the Study: (1) book, (2) iPad, (3) notepad, (4) mug, (5) paper tray.

We selected a conventional tabletop system, in which users can move and lift occluders to cope with physical occlusion problems, to serve as the baseline condition. While it may seem that the comparison with this baseline favors the proposed techniques, in a pilot test we observed that moving and lifting everyday objects is easily performed and can be as fast as dragging out occluded objects. We opted not to compare ObjecTop with prior systems or techniques [e.g. 4, 5] because moving and lifting physical occluders is the most direct and most intuitive strategy to cope with occlusion and this has not examined in previous work. Thus, it is valuable to formally compare these two techniques and identify their respective advantages and disadvantages in depth. We also added a third restricted ObjecTop condition in which participants could not move occluders to simulate interaction with heavy or bulky occluders that cannot be easily moved (e.g., screens, desk lamps, plants, or piles of books, folders and documents) or where the specific location of the object serves other purposes (e.g., a keyboard positioned in a comfortable location for typing).

Experimental Conditions and Hypotheses

- *Classic*: conventional tabletop system. Users could freely move and lift physical objects within the tabletop screen space, although stacking physical objects onto each other was not allowed. Users could manipulate digital objects using common touch gestures (move + pinch).

- *ObjecTop Move*: same as classic condition but ObjecTop techniques could be used.

- *ObjecTop Immoveable*: constrained ObjecTop version with immovable physical objects.

Compared to conventional tabletop systems, we anticipated that both ObjecTop conditions would improve overall performance of finding and structuring digital objects, particularly in high cluttered hybrid settings. Our specific hypotheses are:

H1: Finding digital objects using occlusion-aware techniques in both *ObjecTop* interface conditions will be faster than with the classic interface.

H2: Both *ObjecTop* interface conditions will outperform classic interface while organizing digital objects.

H3: *ObjecTop Move* condition will significantly decrease interaction with physical objects compared to the classic condition.

Tasks

The experiment consisted of two tasks: a search and a layout task. In the search task, participants were asked to find and count specific types of target virtual objects among a number of distracters. One to three target objects were randomly chosen. The targets were uniformly distributed across all tabletop zones (storage and working zones [10]) and were fully occluded in all trials. For this task, we only enabled system features related to awareness and accessing occluded objects.

In the layout task, participants were asked to first find three target objects across a set of physical and digital distracters. They then had to move two of them and place them on two containers displayed with a virtual, faded-out preview of the target objects (cf. Fig. 5 dashed red objects). The third target object had to be hidden under the physical book. To indicate the hiding action, we placed a faded-out printout of the third target on the book during this task (cf. Fig. 5 solid red object). The location of the containers and the physical book were the same in all trials. In addition to occlusion-aware accessing and awareness techniques, we enabled teleport and hiding gestures in ObjecTop Move and Immovable conditions. For the study, we ignored the docking and Exposé techniques because of the lack of equivalents in the touch user interface.

We manipulated the number of digital distracters as well as physical objects to vary the level of clutter. In earlier interviews, 5 individuals were asked to rank the complexity level of hybrid tabletop settings that included both digital and physical objects. Based on these interviews we defined clutter to be a function of the number of digital (ND) objects on a tabletop and the extent to which display surface is covered with physical objects (PO). For our experiment, the low clutter condition consisted of 10 digital objects in which 5 were occluded using 3 physical objects (PO ~40%). The high clutter condition involved 15 digital objects of which 10 were occluded using 5 physical objects (PO ~60%). There were no digital-digital occlusions.

In both tasks, for physical items we used a thick book, a thin paper notepad, an iPad (in keyboard stand position) in the low clutter condition. In the high clutter condition, an A4 paper tray containing a pile of paper and a coffee mug were added. A schematic view of the study setup is depicted in Fig. 5. The digital items were photos, documents, and Post-it notes.

Participants

17 unpaid participants (1 female, all right-handed), age 23-38 (M=28.3, SD=4.3) were recruited from our institution. All had experience with touch interfaces but only 2 had experience with interactive tabletops.

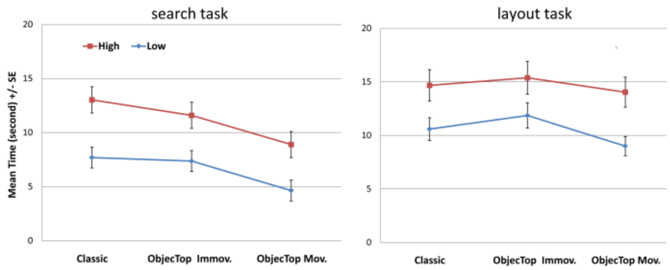

Figure 6. Task Time Performance

Experimental Design

The experiment employed a 3 interface (*Classic, ObjecTop Mov and Immov*) × 2 task (*Search and Layout*) × 2 clutter level (*Low and High*) within subjects design. Our main dependent measurement was trial completion time. It was measured by pressing the spacebar of a keyboard placed on the margin of the tabletop and within arm's reach of participants. In the search task, participants advanced to the next trial regardless of whether their answer was correct or not. We recorded all actions and movements of digital objects in a time-coded log file for subsequent analysis. The perceived workload of each interface condition was measured with the standard NASA-TLX questionnaire [8].

Each participant completed the three interface conditions. Order of presentation was counterbalanced. In each condition, the search task was performed first, followed by layout task. Each task trial block consisted of two low and high trials repeated 5 times each. The trial representation within each session was randomized. High or low scene was the same across conditions and participants. The appearance of low and high clutter trials was also the same across all interfaces and participants. Prior to each interface condition, participants received a short introduction about the system and task and were asked to perform it as quickly and accurately as possible. In ObjecTop Move and Immovable conditions, participants had 10 minutes time to practice the techniques. Before starting each interface condition, there were 4 training trials. After the completion of each interface, a semi-structured interview was conducted to gather subjective feedback. All sessions were videotaped. Each session lasted approximately one hour.

RESULTS AND DISCUSSION

Excluding training trials, there was a total of 1020 trials (17 participants × 3 interface conditions × 2 clutter levels × 2 tasks × 5 repetitions). We had to repeat 84 trials due to the system's failure to recognize tags.

We processed the data to identify and remove outliers (i.e. task time greater than 3 SD away from the mean time) and mistrials (i.e., incorrect answers in search task). In total, we removed 18 trials from the layout task and 15 from the search task. In the following analysis, we used Bonferroni corrections for all post-hoc tests. We found that presentation order of the task blocks had no significant effects on the task time (no learning effect). Our primary

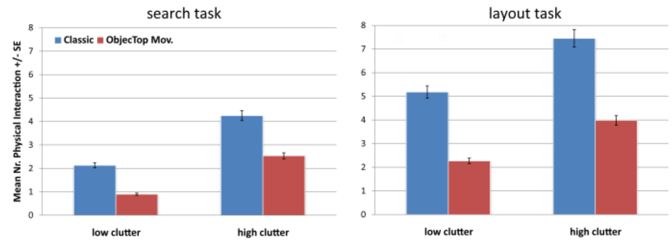

Figure 7. Interactions with Physical Objects

interests are how the interfaces performed in terms of time performance, number of interactions with physical objects and the perceived task load.

Task Time Performance

A 2-way repeated measures ANOVA on the factors of the tabletop interfaces and clutter level for the search task identified main effects for the tabletop interface as well the clutter level ($F_{(2,32)}$ = 2,17, p<.001 and $F_{(1,16)}$ = 4,785, p<.001 respectively). Pair-wise comparison revealed that *ObjecTop Move* was significantly faster than the classic and *ObjecTop Immoveable* conditions (p<.001 and p<.01 respectively). We found no interface×clutter interaction ($F_{(2,32)}$= 3,043, p=.069). Further examination of each clutter level showed that ObjecTop was significantly faster than both *classic* and *ObjecTop Immoveable* for the low clutter level (p<.001 and p<.01). For the high clutter level, both *Move and Immoveable ObjecTop* conditions were significantly faster than the *classic* condition (p<.001, p<.05 – see Fig. 6 left).

For the layout task, a 2-way repeated measures ANOVA identified the interface ($F_{(2,32)}$=7,133 p<.01) and clutter ($F_{(1,16)}$=4,93 p<.001) factors as main effects. Pair-wise comparisons showed that the *ObjecTop Move* interface was significantly faster than the *ObjecTop Immoveable* interface in both low and high clutter levels (p<.05, p<.05 – see Fig. 6 right). We found no other significant differences.

The results of trial time completion revealed that search time using the occlusion-aware techniques in addition to moving obejcts (*ObjetTop Move condition*) was significantly less than with the *classic* tabletop interface. This supports our first hypothesis. However, in layout task, the time needed to recall and perform the gestures was longer, particularly in *ObjecTop Immoveable* compared to *classic condition*. Thus H2 is not supported.

Interactions with Physical Objects

We analyzed the log data and calculated number of interactions (moving or lifting) with physical objects for ObjecTop Move and classic interface conditions. In both tasks, we found main effects for both interface and clutter factors. Statistics are summarized in Table1. Post-hoc comparisons for both tasks showed that ObjecTop significantly reduced the number of interactions with physical objects in both low and high clutter levels (each with p<.001 – see charts in Fig. 7). Since with the objecTop Move interface participants could cope with

task	factor	F-statistics	sig.
search	interface	$F_{(1.16)} = 100.461$	P<.001
	clutter	$F_{(1.16)} = 15.030$	P<.001
	interface x clutter	$F_{(1.16)} = 0.365$	P=.554
layout	interface	$F_{(1.16)} = 20.659$	P<.001
	clutter	$F_{(1.16)} = 26.851$	P<.001
	interface x clutter	$F_{(1.16)} = 4.857$	P=0.133

Table 1. Statistics of Physical Object Interactions

occlusion either by moving or using system support, we analyzed log data to see how individual physical objects were manipulated in this condition. We filtered out movements (less than 5 mm) of physical objects caused by inapporopiate recognition of markers. A summary of the number of interactions with each object is given in Table2. The book and paper pile tray were moved much less frequently than the notepad and coffee mug.

Overall, the results demonstrate that occlusion-aware techniques helped participants to cope with occlusion, requiring fewer physical interactions in both search and layout tasks. Therefore, H3 is supported.

Task Load Index

We collected the perceived workload data using a scale of 1-20 (1 is least effort) for various types of workloads: mental effort, physical effort, temporal demand, performance, overall effort and frustration. A 1-way repeated measure ANOVA found the interface to be a main effect on physical effort, overall effort, frustration and performance (see Fig. 8). Post-hoc pair-wise comparison with Bonferroni correction revealed that the classic condition caused significantly more physical (M=14.5, SD=3.6) and temporal (M=12.64, SD=3.06) effort than the ObjecTop conditions (both with p< .001). This resulted in significantly higher overall effort (M=13.5, SD=2.4, p<.001) with the classic interface. In addition, the classic tabletop condition resulted in significantly higher reported frustration (M=12.9, SD=2.48, p<.001). We found no other significant differences.

id	items	size	low			high		
			Nr.	Mean	SD	Nr.	Mean	SD
1		23 x 19 cm	43	2.8	3.2	34	1.9	2.3
2		24 x 18 cm	53	3.5	3.6	28	1.8	1.6
3		18 x 13 cm	84	5.6	3.4	65	4.3	4.6
4		5 cm (diameter)	-	-	-	48	3.2	2.1
5		30 x 22 cm	-	-	-	35	2.3	2.2

Table 2. Physical Object Usage in ObjecTop Move Condition. (Nr.: the number of physical interactions with each object, Mean: mean value and SD: standard deviation of Nr.)

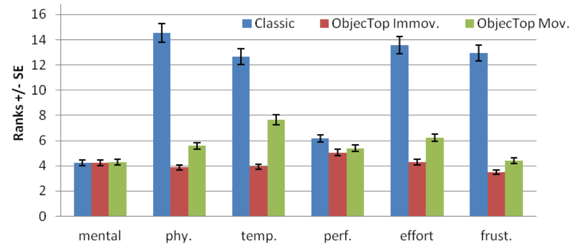

Figure 8. Perceived Task Load of each Interface

LESSONS LEARNED

What is the best strategy?

The study demonstrates that the physical properties of occluders significantly influence how participants deal with occlusion. In order to cope with occlusion, they prefer to move or lift physical objects that are lightweight, easily graspable and have a small footprint (e.g. the coffee cup or notepad). However, for complex and heavier objects (e.g. the book or pile of paper) they preferred using ObjecTop digital access. In addition, physical objects that are placed in the storage areas (outer areas on the tabletop surface at a distance from the user) are less frequently moved, and participants mainly used ObjecTop functionality to access occluded objects, even though they had the option to lift and move occluders. The ObjecTop system enabled participants to employ an efficient combination of strategies based on the physical properties of the occluder and current layout. This resulted in less physically demanding interaction with objects, lower perceived effort and frustration while manipulating digital objects.

Participants mentioned that the system provides a sort of (P11) "*structured access*" to the occluded objects and (P1) *"decreased number of unecessary interactions with physical and digital objects."* P10 said *"all physical edges of occluders become a kind of taskbar where I can spatially organize and minimize my digital objects."* We observed though that once a large number of digital objects were occluded under a physical one, participants preferred physical access by lifting or moving the occluder regardless of its size. A possible reason for this might be that dragging out a large group of digital occluded objects in our system design required more free space around the physical occluder. The study findings indicated that there are conditions in which each of the resolving strategies (physical interaction and digital pulling out) is preferred and practical. In addition, we suggest a third strategy to resolve occlusion. It employs manipulating physical objects and digital access concurrently. As a concrete example, imagine that as soon as the user partially lifts the occluder to peek under it, occluded digital objects slide out visualized as icons. In this way, space created by partial lifting of the occluder can be used for representing occluded digital objects. This helps with the lack of adjacent space problem discussed above.

Quality of the system reaction

In interviews, we asked participants about the amount of visual clutter introduced by halos and icons and the extend to which they found it distracting. Almost all participants (15 out of 17) agreed that the amount of added visual clutter is acceptable in a low clutter level. P16 said *"it helps somehow to make my digital information space even more tidy by quickly hiding, moving and iconizing the objects. It results in more tidy setup."* However, in a high clutter level, participants were sceptical about the amount of visual clutter and proposed some improvements. Five participants commented that the system reaction to and level of awareness about the occluded objects should be somehow under the user's control and manually adjustable (e.g. for the whole tabletop or even one occlusion group).

Where to visualize occluders?

The interactive halo design places an icon on the halo closest to the center of the occluder's footprint. The assumption underlying this design decision was that it implicitly conveys spatial information about the location of the occluded object. However, during the study we observed that participants mainly used the group access gesture (N=443, mean=29.53, SD=17.3 per participant in the whole study) to check all objects occluded underneath one occluder, instead of looking at just one occluded object. In interviews, 13 participants stated that the icon placement on the halo should be towards the user. They emphasized that this is particularly important for occlusion groups that are located on distant areas of the tabletops or for volumetric objects that occlude more tabletop space from the user's view than just their footprint (e.g. a laptop while the lid is open). Doing this may decrease the effort required to look for icons. However, several participants commented that they prefer our original design for smaller and lightweight occluders, since a representation close to original location of the occluded items provides a hint about its approximate position and makes it easier to move the occluder in a way to best access the occluded object. Gradual and remote access

With respect to gradual access, we observed that participants rarely used intermediate detail levels while accessing individual items. Analysis of the videos revealed that accessing the various detail levels of an individual item requires a fine-grained action but was mapped to course dragging out gesture. Applying hysteresis to maintain each detail level for a longer duration while dragging out may alleviate this problem. Participants however frequently used zooming for the group access since it enabled a peek under the space covered by physical occluders.

Remote access was mainly used in the ObjecTop Immovable condition, since participants were not allowed to move physical objects. Using remote gesture, participants occasionally resolved occlusion groups that were located on more distant tabletop areas (storage areas). Nevertheless, in interviews participants generally appreciated remote access and commented that it can be useful when the arrangement of the physical objects should be maintained (for instance a spatially sorted arrangement of a set of documents). This can be expected to be more frequent in everyday information organization tasks.

Organizing the hybrid workplace

We analyzed how participants interacted with digital objects in the layout task. We observed similar patterns in the ObjecTop move and classic conditions: participants organize digital objects using conventional touch gestures and manually freed the path while dragging the digital item to its target position. In contrast, in ObjecTop with immovable occluders, participants used either the gestures (teleport and hiding) or moving digital objects around the occluders. This caused longer task completion time in ObjecTop immovable condition. Discussion with participants revealed that the organizational gestures (teleport, hybrid hiding and binding) are only practical for interaction with digital objects located on storage areas of the tabletop.

We observed that participants used teleport gesture more (N=141, mean=9.4, SD= 5.3) than the hiding technique (N=36, mean=2.4, SD= 2.5). A common pattern was that they first moved digital objects near to an occluder using teleport and then simply hid them by pushing them beneath the occluder. Discussion with participants revealed that hybrid hiding and binding gestures needed more visual focus and hand coordination. In contrast, participants mentioned that the teleport gesture is much easier to perform since *"you just need to find or make an empty spot to place the tripod gesture and then that's it" (P 6)*. Five participants even suggested extending the teleport gesture to be performed on physical occluders for hiding objects underneath them by placing tripod-like three finger gesture atop the physical object.

Occlusion-aware techniques in multi-user settings

Although presented techniques are implemented for and studied in a single-user tabletop setting, they can be easily extended to support collaborative scenarios, e.g. meeting scenarios where multiple users sit around a digital tabletop working with multiple physical and digital objects. Once occlusion happens in the shared space of the tabletop surface, the halo and icon representation can be extended in a way that provides orientation-invariant access to the digital objects. As a concrete example, the halo can provide strong visual clues on each corner of the occluder to enable group access to occluded objects from four directions. Moreover, since the system knows the position of the user dragging out the halo, it can visualize the various detail levels of occluded objects in an appropriate orientation.

The occlusion-aware organizational gestures can also be extended to *cooperative gesturing* [24] in multi-user settings. This may enhance collaboration as well as facilitates reachability and access across large surfaces.

Future work is needed to investigate issues related to cooperative gesturing in hybrid tabletop settings.

CONCLUSION

Hybrid tabletop settings pose challenges for both display and interaction. Physical objects may hide or partially occlude digital items, resulting in users being unaware of the presence of occluded items, making access to them difficult, and restricting screen areas for display and interaction. Since it is reasonable to expect that tabletop display surfaces will increasingly become part of everyday life, understanding how to provide practical solutions to the challenges of occlusion is important. The ObjecTop system implements a collection of occlusion-aware techniques to support users while interacting with digital and physical objects on tabletop display surfaces. These techniques provide awareness, access and interaction with occluded digital objects. We report an evaluation of ObjecTop compared with a conventional interface that demonstrates it is faster for finding objects, decreases interaction with physical objects when resolving problems of occlusion, requires less effort, and is less frustrating.

ObjecTop interaction facilities are examples of providing what one might term an *informational physics* for digital elements [1]. Just as the simple physics of snap-dragging is valuable when positioning items on a grid, one can envision a variety of informational physics designed to support specific tasks while being sensitive to the current activity context and the hybrid collection of digital and physical objects. The challenge is to support information-based activities in ways that increase not only efficiency but also enjoyment of interaction.

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