SleeD: Using a Sleeve Display to Interact with Touch-sensitive Display Walls

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Figure 1. SleeD prototypes: e-Ink mockup (left), smartphone-based prototype showing tool palette (center) and interactive personal view (right)

ABSTRACT

We present SleeD, a touch-sensitive Sleeve Display that facilitates interaction with multi-touch display walls. Large vertical displays allow multiple users to interact effectively with complex data but are inherently public. Also, they generally cannot present an interface adapted to the individual user. The combination with an arm-mounted, interactive display allows complex personalized interactions. In contrast to hand-held devices, both hands remain free for interacting with the wall. We discuss different levels of coupling between wearable and wall and propose novel user interface techniques that support user-specific interfaces, data transfer, and arbitrary personal views. In an iterative development process, we built a mock-up using a bendable e-Ink display and a fully functional prototype based on an arm-mounted smartphone. In addition, we developed several applications that showcase the techniques presented. An observational study we conducted demonstrates the high potential of our concepts.

Author Keywords

multi-touch; display wall; wearable display; multi-user; collaboration; information visualization; arm display

ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces - Graphical user interfaces.

INTRODUCTION

Wall-sized interactive displays are becoming more common and have been shown to provide numerous benefits [2]. Their potentially very high resolution means that they are usable from a distance as well as in reach of the hands, making them suitable for the exploration of large amounts of data. Collaboration is well-supported and physical navigation – moving around to access data – becomes possible, exploiting human spatial awareness [5]. At the same time, they have inherent limitations. Data shown is generally visible by all collaborators and thus public. It is hard to identify the user and provide a user-specific interface. In addition, it is unclear where user interface elements such as tool palettes should be placed on a very large display [2].

In contrast, the most widespread type of computing device – the smartphone – is an inherently personal device that connects users with their digital ID, providing easy access to private data in everyday situations. Due to their small size, smartphones have limited ability to show large amounts of data; also, sharing views with other people is hard at best. Furthermore, hand-held devices cannot be used in situations where both hands must be free, leading to devices such as the Motorola WT4000 arm-worn terminal used by warehouse workers [30]. The recent trend towards smart watches (such as the Sony SmartWatch 3 or the Apple Watch) points in the same direction and showcases a second benefit: quick, effortless activation of the device.

Numerous researchers have combined smartphones and other hand-held devices with shared displays in the past (e.g., [20, 24, 26, 27, 29]). This makes it possible to use the modalities – display output, touch input, sound and haptic feedback – available on the personal device to extend interaction with the large display. It also allows personalized interaction and access to private data when using the large display.

We propose combining large display walls with a touch-enabled sleeve display – the *SleeD*. Using an arm-mounted device in combination with a wall-sized display is novel and provides unique additional benefits. First, touch interaction with a wall is one of the situations in which having both hands

ITS 2014, November 16–19, 2014, Dresden, Germany.

ACM 978-1-4503-2587-5/14/11 ...$15.00.
http://dx.doi.org/10.1145/2669485.2669507

free is advantageous, because it allows bimanual interaction. Second, interaction becomes seamless and facilitates a quality of *flow*: When the user touches the wall, the hand assumes the role of conduit between personal data on the SleeD and public data on the vertical display (see Figure 1). Third, arm-worn devices support *effortless activation* [3]: While the SleeD is available at the flick of a wrist, hand-held devices must be retrieved from pockets or other storage, making it much easier to integrate the device into other activities.

Our individual contributions in this paper are:

- The SleeD Concept: This includes physical considerations such as placement and properties of the display as well as an analysis of different levels of coupling between SleeD and wall. We also present a range of novel user interface techniques that support modal interfaces and provide personal storage as well as personalized views.
- Prototypes: We present two wearable hardware prototypes. The first one is non-interactive and based on a bendable e-Ink display. The second is realized using a conventional smartphone attached to the arm. In addition, we present several software applications based on the second prototype that showcase the concepts and techniques described.
- User Study: We report on an observational user study that shows the high potential of the concepts and techniques.

In the following, we present the proposed SleeD device and two scenarios illustrating typical usage, followed by reviewing related work. Underlying concepts are described in the subsequent section, followed by a description of the prototype hardware and software. We then describe the conducted user study and conclude with an outlook to future work.

SleeD

We envision a wearable arm display covering most of the forearm in length and circumference (see Figure 2). The device is an unobtrusive, lightweight system with a touch-sensitive high-resolution color display. It otherwise has the input and output capabilities of today's smartphones, including accelerometers and vibro-tactile feedback as well as audio in- and output. SleeD is not significantly more cumbersome than normal clothing, allowing everyday use. We see it fulfilling several roles.

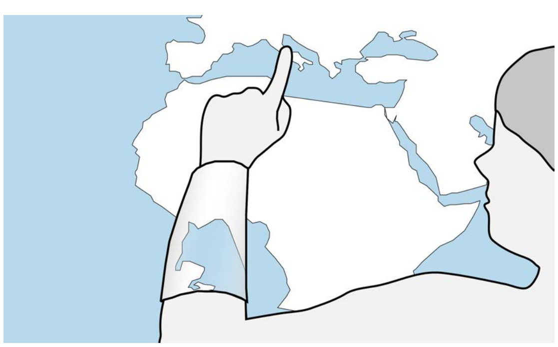

Figure 2. SleeD concept: Use in a geographical application

First, SleeD is a *personal device* that provides arbitrary applications and allows access to personal data, similar to today's smartphones. Following Martin [18], the development of smartphones could well mimic wristwatch development: Once the weight of the device is reduced sufficiently, the benefits of effortless activation and hands-free usage come to the fore. A second role – again, hinted at by the development of the wristwatch [18] – is that of a *fashion accessory*. In addition, we foresee a third role: The SleeD can greatly *enhance interaction with other devices*, among them large interactive displays. It serves as a conduit between personal and public data. Furthermore, it can provide a personal clipboard and user-specific tool palettes as well as show contextual information – all while allowing bimanual interaction on the large display. In this paper, we concentrate on the third role.

While the envisioned device cannot be built entirely using current technology, ongoing research in the area of flexible displays and circuitry will likely provide the means for such a device in the near future [10].

Walkthrough

In the following, we present two scenarios of typical uses of our envisioned system to illustrate our concept.

I. *Jane works in the field of geoinformatics, often analyzing large geographical datasets. She stands in front of a wall-sized interactive display that shows a map. A SleeD is attached to her left forearm, showing an overview of the entire map. By touching the map on the SleeD, Jane selects the part of the map to be shown on the vertical display. Thus, she can quickly zoom in on an area of interest, benefiting from the high-resolution wall display.*

She then approaches the wall to see more details. When she touches it, the wearable switches to a detail view of the area touched (see Figure 2), leveraging the higher pixel density of the SleeD. Probing is also supported. In this mode, the arm display shows additional data on the current touch point and thus avoids clutter on the vertical display. These personal views are especially useful when John, a colleague of hers, arrives and they work on the dataset in collaboration: By zooming and filtering their personal views, they avoid disrupting the view on the wall. When Jane is ready to share insights, she transfers her personal view to the wall and they discuss the results together.

II. *Mark and Jennifer work for a media company. They use SleeDs in combination with a display wall for selecting and annotating photos. When Mark finds interesting pictures, he touches them with his SleeD hand and uses the other hand to quickly drag them to his personal display. To copy the photos to a different location in the shared workspace, he simply flicks them from the wearable back to the wall. Since the SleeD is mounted on his arm and not a hand-held device, he can seamlessly switch to working with paper artifacts such as printed magazines and photos.*

His colleague Jennifer can quickly change between different editing modes, such as annotating or image manipulation using a tool palette on the SleeD. Still, her hands remain free for bi-manual work on the larger display. Tool palettes and other *context- and mode-sensitive user interface elements are displayed on the SleeD, staying with her as she moves along the wall. Just as importantly, the tool configurations are her personal configurations: When she switches to a tool for color correction, she doesn't interrupt Mark's ongoing work.*

These scenarios showcase several important aspects of the proposed system integrated in an end-user context: effortless activation; quick, lightweight, user-specific mode switches; personal display and storage spaces as well as clipboards; overview-and-detail support; and hands-free interaction on the wall. In comparison to hand-held mobile devices, changing the focus between vertical display and personal device is less cumbersome, because the SleeD does not have to be put away when not actively in use.

RELATED WORK

Our work builds on research in a number of different areas, including large wall-sized displays, wearable computing and interaction of mobile devices with large displays.

Interactive Wall-Sized Displays

Distant interaction with wall-sized displays has been investigated at least since Krueger's Videoplace [15]. More recently, when wall-sized displays reached resolutions in the tens and hundreds of megapixels, they again became a research focus, most prominently in the areas of information visualization and analysis. For an overview we refer to Andrews et al. [2], who describe the state of research. Among others, they identify precise selection at multiple scales and placement of control panels as research issues, suggesting hand-held devices as one possible solution. They stress that interaction effects should be "localized based on the user's position and focus."

Wearable Computing

The commercial trend towards miniaturization discussed in the introduction also finds itself in scientific work on wearable forearm devices. Closest to us is Olberding et al.'s work on display-enhanced forearms [22]: they suggest a display on the upper side of the forearm and explore the interaction space, using the user's sleeve to control visibility of display portions to the public. With Facet, Lyons et al. [17] present a multi-display system circling the wrist. Tarun et al. [31] proposed using flexible display devices that could be used both hand-held or as a wristband, adapting its user interface to the current configuration. These papers did not consider multi-device interaction, something that we focus heavily on in combining the SleeD with an interactive wall-sized display. Recently, Chen et al. [8] used a smart watch in conjunction with a smartphone. While our approach consists of a very different setup, some of their techniques could potentially also be included in our system.

An early precursor to our body-centric approach to interaction with the SleeD is found in Pierce et al.'s work on Toolspaces [23], where tools in a virtual world are placed in fixed positions relative to the user's body. More recently, Harrison et al. [12] used the skin of the arm as a touch input device, combining it with a pico-projector to project a user interface. Again, multi-device interaction is not considered.

Mobile Devices and Large Displays

Interaction between hand-held devices and large displays has been studied numerous times, mostly with a focus on individual interaction techniques. Early work was presented by Rekimoto [25] who used hand-held computers as personal devices for collaborative work on digital whiteboards, supporting private clipboards and tool palettes.

More recently, significant work by Schmidt et al. [26, 27] examined cross-device interaction between phones and interactive surfaces. They proposed a collection of interaction techniques in areas such as data transfer, personalization, or localized feedback. This research is expanded upon by Seifert et al. [28], who investigate UI mechanisms for moving data from a mobile phone to a table. One of the issues they identified is that "only one hand is available for interacting with the table" while holding the phone. In contrast, our approach keeps the user's hands free, allowing bimanual interaction on the display wall. Using a mobile device to personalize interfaces was also investigated by Spindler et al. [29], who offload user interface palettes onto secondary hand-held displays and thereby free the associated display space. Similarly, Adachi et al. [1] proposed a forearm menu in combination with a tabletop. However, both approaches are projection-based and thus limit the interaction space and display fidelity in comparison to our work. The idea of using mobile personal palettes is also found in Haller et al.'s work on the NiCE Discussion Room [11], who use pen interaction with static, palm-sized printed menus to interface with a large interactive whiteboard.

A different variant of personalized interfaces is presented by Voida et al. [33]. They combine a tabletop and a hand-held device for focus-context interaction, using the hand-held to display a focus lens. Beaudouin-Lafon et al. [6] present a similar setup using a tablet and a wall. Daiber et al. [9] combine a cell phone attached to the back of the user's hand with a tabletop display to enhance a map viewer, displaying map contents on the phone. In contrast, our approach uses a wearable display and supports additional interaction techniques for personal clipboards and tool palettes.

Summarizing the above section, we build upon a rich set of techniques that have been explored in the context of interaction with mobile phones, contributing the first work that uses a wearable device in combination with a wall-sized display.

CONCEPTS

In this section, we delineate the proposed SleeD concepts in more detail. We identify basic physical considerations and analyze the levels of coupling available when combining the two devices. Furthermore, we propose a number of novel UI techniques that support multiple users, personal storage and the ability to display additional personal views.

Physical Considerations

In general, we assume that SleeD will be worn on the non-dominant arm, allowing the dominant hand (DH or non-SleeD hand) to interact with it. Both hands are free to interact with the wall; in particular, touches with the non-dominant hand (NDH or SleeD hand) can be used as a frame of reference for interactions on the SleeD. Possible configurations are devices that are worn below, above, or as part of the clothing.

We find Wagner's distinction of interaction into the categories *relative to the body* and *fixed in the world* [34] to be useful in describing multi-device interactions. Accordingly, we use a *body-centric* reference frame to describe positions on the arm-mounted display, with the proximodistal dimension along the arm and the axial dimension around it (see Figure 3) and propose using a separate *wall-centric* reference frame that is fixed in the vertical display. We suggest using the arm's proximodistal dimension to signify connectedness with the wall: The distal region (near the hand) shows data or widgets with a strong relationship to the wall, while the proximal region can show SleeD-specific items such as personal data or general menus. Additionally, it may be advantageous to offer a user interface that allows users to rotate its contents in the axial direction. This is particularly interesting for vertical menus, where the curvature of the arm provides a natural focus and items on the top and bottom serve as context.

Also, in contrast to conventional displays, only parts of the SleeD are visible to the user at any point in time. In particular, the anterior region (inner side of the arm) will generally be inaccessible when the SleeD hand is touching the wall. There are other differences between the posterior (outer side of the arm) and anterior regions as well: The anterior region is less visible to others; also, more physical effort is required to view and interact with its contents. This should be taken into account when designing interactions.

An important consideration in multi-device interaction with large displays is minimizing the number of gaze shifts [24], and the trade-off between placing UI elements on the wall or the SleeD should be carefully considered. Since the SleeD's position on the user's arm is fixed, we can leverage proprioception (the perception of the position of one's own body parts) to enable eyes-free interaction on the SleeD. For absolute positioning, we can exploit the fact that users are able to reliably discriminate and touch up to six different points on their forearm [16]. Precise relative positioning is possible without restrictions [32].

Multi-device interaction also needs to allow for differences in the capabilities of the displays. Most importantly, resolution differences need to be taken into account. In our case, this means that the SleeD will be able to display a comparatively large amount of data despite its small display size. An additional consideration is color reproduction: Displays often have very different color fidelity, making it hard to compare two views on different devices.

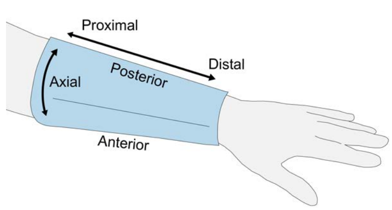

Figure 3. Body-centric view of the SleeD

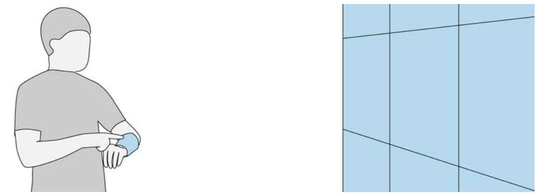

Figure 4. Logical Coupling: Interaction from a distance

Coupling Modes Between SleeD and Wall

Focusing again on the combination of a wearable display with a large display wall, we identify different levels of coupling between these devices. They are characterized firstly by the physical and logical distance between wall and SleeD. Second, it matters whether touch interaction with the vertical display uses the SleeD hand or the other. We propose distinguishing between *decoupled*, where the SleeD is used independently of other devices; *logical coupling*, signifying wall interaction from a distance; *loose physical coupling*, where only the non-SleeD hand interacts with the wall; and *close physical coupling*, meaning that the SleeD hand touches the wall as well. Of these, close physical coupling is the most interesting to us, because it brings forth many of the unique advantages of the envisioned device combination.

Decoupled

In the most basic setup, the SleeD is used in a stand-alone fashion. As described earlier, it replaces or augments today's smartphones and offers much of the same features in this usage scenario with the additional benefits of hands-free operation and near-instantaneous activation as well as being usable as a fashion accessory when not in use.

Logical coupling

When the user approaches a wall-sized display withing viewing range, it becomes possible to use the SleeD to interact with it (see Figure 4). At this point, the SleeD is used in a fashion that is similar to a remote control (with the difference that both hands are free when not directly interacting). Among others, interaction techniques like the distant pointing investigated by Jota et al. [14] and Nancel et al. [20], as well as Nancel et al.'s pan-and-zoom [21] and Seifert's PointerPhone [28] become available. Body-centric and wall-centric reference frames are not fixed with respect to one another, since the user's mobility is unrestricted. Logical coupling is also where frequent gaze shifts between devices were found to impair interaction [24], making eyes-free interaction important.

This level of coupling is likely a transitional state – after all, much of the wall's resolution remains unused because the human eye is unable to perceive the individual pixels from afar. Still, it allows, e.g., general setup of a visualization or the opportunity to step back and get an overview.

Loose physical coupling

In this and the following state, the user is able to physically touch the wall (see Figure 5). While the user cannot see the complete wall, she can perceive all information in her field of view. In loose coupling, the DH interacts with the vertical display, while the NDH with the SleeD does not. This allows the user to rotate her arm, providing access to all parts of the display and maximizing available screen space. Body-centric and wall-centric reference frames are less independent of one another than in the logical coupling state, since the user's movement is restricted with respect to the wall to a certain degree.

Close physical coupling

In this state, the user is touching the wall with the SleeD arm. Body-centric and wall-relative reference frames are fixed in relation to each other; the wearable is easily positioned in relation to the screen. This creates a classic kinematic chain [4] in that the SleeD hand serves as a frame of reference for the non-SleeD hand. For closely coupled touch interaction on the wall, the user's arm rotation is largely given by human anatomy, limiting access to the anterior region of the device.

In contrast to interaction with a hand-held mobile device touching the wall, the display contents remain easily visible in close physical coupling, and direct interaction with the SleeD remains possible (see Figure 5, right). This provides an inherent *quality of pointing*: The SleeD's distal end points at the wall, and the hand can be seen as an extension of the device. Additionally, movement along the proximodistal axis produces a *flow* towards or away from the wall. This can be used in user interface design, for instance by using swipe gestures to move items to and from the wall. We also support this by placing interface elements that are semantically closely related to the wall (e.g., clipboards to transfer data) spatially near the wall as well, in the distal region of the SleeD.

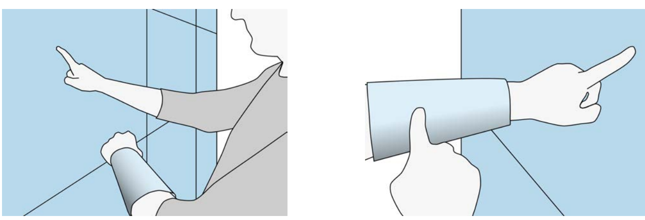

Figure 5. Loose (left) and close (right) physical coupling

User Interface Techniques

Based on the preceding considerations on physical aspects and modes of coupling, we propose a number of specific user interface techniques that leverage the advantages of both devices. These span a number of use cases, among them personal storage and data transfer, user-specific interfaces and personal views and coexist easily in applications. Many of the use cases have been explored before in the context of cross-device interaction between hand-helds and large displays (e.g., Schmidt et al. [27]); we contribute specific, novel interface techniques. Many of them exploit the fact that the SleeD is easily visible in close coupling scenarios to enable a natural flow of interaction.

Local Storage: SleeDTransfer

Since data visible on a SleeD is implicitly personal, we can use it as an interface to personal data collections. In this context, we contribute *SleeDTransfer*, a technique for data transfer between the devices that uses a *drop zone* at the distal end of the SleeD (see Figure 6). Following flow principles, users can drag an item to the drop zone in close coupling to transfer it from the SleeD to the wall. Conversely, touching an item on the wall causes a proxy to appear in the drop zone; dragging the proxy from the drop zone transfers the item. Additionally, in loose coupling, items can be dragged to the drop zone to preselect them for transfer. The actual transfer is then initiated with a touch on the wall. Both move and copy operations can be realized and distinguished, e.g., by using a two-finger drag to signify a copy operation.

The same interaction technique can be used to enable user-specific multi-item clipboards, in effect making it possible to efficiently move items from one position on the wall to another – even when other users are blocking the path. Additionally, the preselection technique allows for a number of items to be made public efficiently with one touch; it also preserves privacy, since the selection happens on the personal device and not on the public display.

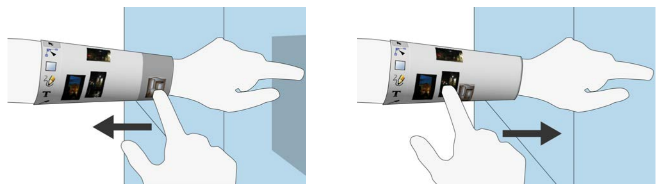

Figure 6. Transfering data between wall and SleeD using *SleeDTransfer*.

User-specific Interfaces: SleeDPalettes and SleeDMenu

A SleeD can be used to present tool palettes (see Figure 7) or other arbitrary interfaces that control the application on the wall. These *SleeDPalettes* have several advantages: They free shared screen space and minimize visual clutter. They can also take a user-specific application state into account, be personalized for their users and show information that should not be visible to others (e.g., PIN code input). Furthermore, they allow user-specific modes. Unlike most palettes on hand-held mobile devices (and, incidentally, traditional painter's palettes), *SleeDPalettes* are always reachable and still allow the user to interact bimanually with the large display, making fast and seamless mode changes an important advantage of wearable interfaces. Similar to the tool palettes, the SleeD can also show a context-sensitive menu – the *SleeDMenu* – when the wall is touched. It activates on the SleeD, its content depending on the touch position's underlying data.

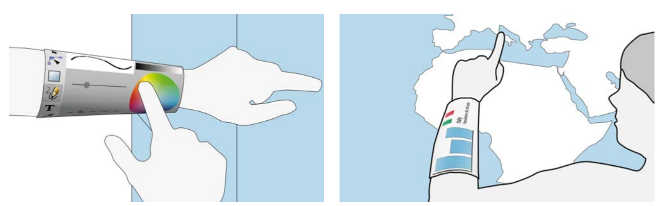

Figure 7. *SleeDPalette* (left) and *SleeDProbe* (right)

Personal Views: SleeDDetail, SleeDLens and SleeDProbe

The wearable provides the user with an additional screen that generally remains visible when the SleeD hand is touching the wall in a close coupling scenario. This enables a range of techniques that particularly benefit collaborative information visualization applications. In particular, we can show arbitrary personal views that change based on the current touch point. In this context, we propose several novel techniques.

With *SleeDDetail*, we contribute an adaptation of Overview and Detail techniques (see Figure 2). While the wall shows an overview of an area (e.g., in a map), the SleeD shows an enlarged view of the area around the touch point. *SleeDLens* generalizes this: We propose showing an arbitrary modified view of the area around the current touch position on the arm display. A touch-based UI on the SleeD allows the user to adjust view parameters. This is novel in that it moves Bier's Magic Lenses [7] to a separate display while still retaining the immediate connection between lens and context through close coupling. In addition, we propose using the personal display for probing in *SleeDProbe*. While exploring a visualization at close range, additional data can be shown specifically for the current touch position (e.g., a country's demographic data, see Figure 7, right), and corresponding audio or haptic feedback is possible as well. Snapshots of this data can be saved to compare different positions.

All the personal view techniques have in common that they avoid cluttering the shared view and allow multiple users to work on the wall without interfering with each other. Working with private data is also possible.

Remote Control: SleeDOverview

In loose coupling, SleeD can be used as remote control. We contribute *SleeDOverview* in this context: While the SleeD shows an overview of available data, the wall shows a detail view. Interaction on the wearable changes the view on the wall. This gives users a powerful way of quickly selecting the data window they would like to work with. This technique also combines very well with the inverse scenario described above: A user can select a detail view from afar, approach the wall to work on this detail view and then show an even smaller part of the data on the SleeD for close inspection.

Precision Input: SleeDCursor

A variation of the *SleeDDetail* technique above provides us with a natural workaround for the well-known fat finger problem: We propose *SleeDCursor*, where the wearable shows an unoccluded view of the area touched on the wall in close coupling. Even the effects of minimal changes in touch position are clearly visible on the arm display, allowing precise positioning in an intuitive way. Moreover, since both hands are free to interact, touch precision can be improved drastically by using the wall touch for a coarse preselection and the SleeD for the actual selection task.

IMPLEMENTATION

We developed the SleeD concept and the associated software in an iterative fashion. Initially, we built several cardboard mockups of arm-mounted displays and solicited comments from in-house HCI experts. Many of the initial concepts and ideas for UI techniques stem from these discussions. We followed up on this by building two hardware prototypes and several small applications in order to further refine the SleeD concept and to verify it. As a large display, we used a wall consisting of twelve 55" multi-touch displays with a total dimension of 5x2 meters and 24 megapixels total resolution. We do not track user IDs in the prototype setup, making it single-user-only at the moment.

Figure 8. Prototype I (Wizard-of-Oz) using a Plastic Logic e-Ink display.

Prototype I

In the early stages of our work, we built a prototype based on a 10.7" bendable display – a Plastic Logic organic e-Ink display[1] – with at 4:3 display ratio (see Figure 8). With a size of 216x163mm and a specified bend radius of 1.5cm, it fits comfortably on an adult forearm when bent around its longer side. The display is lightweight enough to be carried for extended amounts of time. However, the update speed of current e-Ink displays (> 300ms in our case) severely limits possible interactions and touch functionality is not readily available.

Still, since the display's dimensions are very close to the envisioned form factor, the prototype allowed us to conduct initial experiments concerning functionality and placement of UI elements using Wizard-of-Oz-type mockups that heavily influenced the concepts described above. One interesting result of the tests was that, similar to a watch, the SleeD needs to be at least semi-fixed near the wrist for the zone underneath the arm to be usable. The reason lies in human anatomy: Since the forearm's bones twist around each other, a device fixed only at the proximal end of the forearm will not move when the forearm is turned around its axis.

Prototype II

For *Prototype II*, we used a 4.8" 16:9 cellphone – a Samsung Galaxy S3 – and added a forearm mount (see Figure 9). We decided upon this form factor after experiments with a cardboard model of a 6.1" phone: The larger phone is too wide to be used comfortably when attached to the arm. The cell phone hardware, while being smaller and heavier than the envisioned display, allowed us to quickly develop actually usable high-fidelity software prototypes, although we could not test the specifics of a curved display.

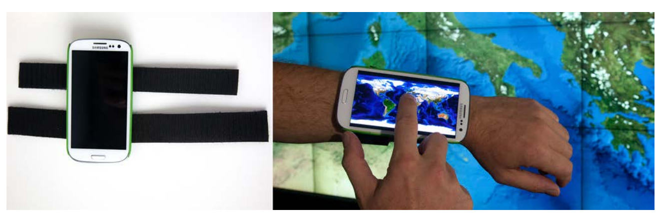

Figure 9. Prototype II based on a Samsung Galaxy S3 phone (left). The map viewer, using the second prototype to show an overview (right).

Applications

We built three applications to verify the user interface concepts. The first is a showcase graphics editor/picture viewer; the others are two map viewers that implement the personal view techniques described above. All software runs on Prototype II, and all applications were built to support left- and right-handed usage. Some of the interface concepts needed

[1] http://www.plasticlogic.com/

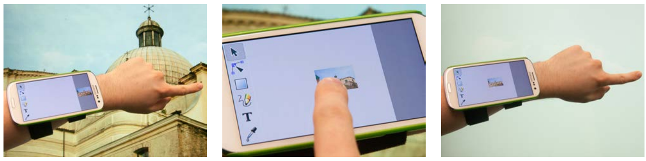

Figure 10. Using the drop zone to move an image to the SleeD.

to be adapted to the smartphone form factor: The display is smaller and planar, providing less room for output and exacerbating the fat finger problem. However, it still allowed us to test most of our concepts with today's hardware.

Graphics Editor/Picture Viewer

The first application integrates two distinct modes and explicitly supports the quality of *flow*, mentioned earlier. In the first mode, it acts like a typical multi-touch picture viewer with additional private multi-item clipboard support on the SleeD. *SleeDTransfer* is fully implemented: Transfer to and from the wall using the drop zone at the *distal* end of the device as well as preselection functionality are available (see Figure 10).

Figure 11. Fingerpaint mode (left) and its tool palette (right).

The second mode allows fingerpainting, implementing a tool palette on the SleeD (*SleeDPalette*, see Figure 11). In this mode, users can paint by touching the wall. They can select colors using an HSL-based color chooser and select the line width using a slider. A vertical menu at the *proximal* end of the SleeD allows switching between the two modes.

Figure 12. Map viewer showing a detail view (left) and probing (right).

Map Viewers

In the two SleeD map viewers, we implement the Personal View techniques presented above. We used gigapixel-sized NASA Blue Marble images[2] for the maps; additional data came from NASA Earth Observatory[3] images.

The first map viewer shows a world map on the SleeD and a detail view on the wall (see Figure 9, right). It is designed to be used in *logical coupling mode*, at a distance from the wall.

The second one shows the world map on the wall and implements *SleeDDetail*, *SleeDLens* and *SleeDProbe* functionality in three separate modes. In all of them, the data displayed on the SleeD changes based on the geographical location touched on the wall. In *SleeDDetail* mode (see Figure 12, left), the SleeD displays a detail view of the world map. In *SleeDLens* mode (see Figure 1, right), it displays a map with global temperature data localized on the touch point. Using a slider, users can select which year of temperature data to display. Finally, in *SleeDProbe* mode (see Figure 12, right), the SleeD displays a bar chart with data (cloud fraction, vegetation and vegetation CO_2 intake) for the current touch point.

Realization

All applications were implemented using the libavg framework[4] and all application-level code was written in Python. The application runs on a single dual-processor Xeon workstation that drives the twelve wall displays. SleeD display contents are generated on this machine as well using offscreen rendering. A custom libavg plugin encodes them using jpeg compression and streams them to the SleeD, where they are decompressed by a small java app and displayed. Conversely, touches on the SleeD are streamed to the workstation and fed into the libavg input framework. Since the plugin runs in a separate thread, application performance is not impacted.

To show the gigapixel images, we built a second libavg plugin that handles image pyramids. It loads the tiles needed on-demand using a thread pool of jpeg loaders and uses an LRU cache to avoid reloading when possible.

USER STUDY

To verify the SleeD concept, we ran an observational study in a laboratory setting using the phone-based prototype and our display wall. The study was designed to investigate a broad range of user interface techniques and concepts, thus providing maximum insight into their usefulness and acceptance. At this stage in development, we were mainly interested in qualitative feedback. Seven unpaid participants (male, aged 23-40) volunteered for the study. Two of them had minor experience with an interactive display wall and one had used a smart watch. No others had used wearable computers before.

Study Procedure

The study consisted of individual sessions of about 45 minutes per participant. We videotaped the study and took notes. After obtaining informed consent, we gave each participant a short introduction to the SleeD concept and let them fill out an initial questionnaire about their background. The interaction with the prototype itself consisted of a diverse selection of the most important tasks, with a short explanation of the available functionality and usage given before each task:

- *SleeDTransfer*: Participants were asked to sort around 20 photos on two axes using the clipboard functionality. Sort criteria were lightness for the horizontal axis and the amount of water displayed in the image for the vertical axis. Since we wanted to focus solely on the new functionality, we asked the participants not to drag the images on the wall directly.
- *SleeDPalette, SleeDMenu*: We asked users to switch to drawing mode, trace an image displayed on the wall using the arm display to change colors, switch back and move the image away.

[2]http://visibleearth.nasa.gov

[3]http://earthobservatory.nasa.gov

[4]http://www.libavg.de

- *SleeDOverview*: Using an overview map on the SleeD and a detail image on the wall, participants had to navigate to three self-chosen places.
- *SleedDetail, SleeDCursor*: Participants were asked to follow the river Nile from its mouth to Lake Victoria using the second map viewer (overview on the wall). They had to repeat this task four times in counterbalanced order, once for each combination of possible SleeD arm and active hand.

After each task, we solicited comments and initiated a discussion about the tested functionality. Finally, we asked each participant to fill out a second questionnaire containing 16 five-point likert scale questions and free-form comment fields on: NASA TLX-based task load, the concepts, and the realization of the prototype. In the comment fields, participants were asked to list positive and negative aspects of both concept and prototype.

Results

In general, the feedback we received was very encouraging (see Figure 13). The quantitative questions on the concept all had an average rating of better than 2 (1=very good, 5=very bad). In particular, participants thought the concepts were very useful (1.29). Physical demands were rated at 1.86 on average (1=very low, 5=very high). The answers on prototypes ranged on average from 1.9 to 2.7 (1=very good and 5=very bad). These quantitative results were very promising but should not be over-interpreted due to the small sample size. More importantly, we collected rich qualitative feedback by evaluating the videos, the questionnaires and the notes taken during the sessions.

With very few exceptions, interfaces were usable on the first try after a short explanation without live demonstration. Three participants made explicit positive comments on the smoothness of the prototype interface (Participant S3: The prototype *"felt real and natural, very smooth interaction"*). S6 noted that the *"interaction techniques were very well designed"* and S4 spoke of a *"very cool concept"* in general.

Photo Sorting

In the photo sorting tasks, *SleeDTransfer*, the natural flow and the concept of the drop zone were commented on favorably (e.g., S5 spoke of a *"seamless transition between personal space and wall"*). Private storage was used extensively, with many participants picking up a number of similar images and dropping them sequentially in the destination area. S6 remarked that preselection *"made it really easy to move a lot of objects at once, especially if I had to place them far away."*

S2 and S3 found sorting on the SleeD to be hard because of the small display, pointing to the advantages that an arm-sized device would have. S6 would have liked the ability to pre-sort items on the SleeD, then drop the finished layout on the wall.

Map Viewer

In the *SleeDDetail* task (Nile tracing), preferences for the different configurations were not very strong: Three subjects preferred loose coupling with the dominant hand touching. The other three combinations of touching hand and coupling were each preferred by one participant, and one participant was undecided. S2 commented that it was easier to hold the arm display steady in loose coupling configurations.

Regarding *SleeDCursor*, S5 commented that showing detail on the SleeD solves the occlusion problem. Also, two participants were surprised by the ease with which precise positioning was possible by rolling the finger, while three participants that did not discover this technique commented on imprecise positioning, and one participant changed his mind mid-task. Hence, it seems probable that the technique is very effective but has a small learning curve.

Issues of Perceptual Transition

In the drawing task, participants found it difficult to choose the right brush parameters on the SleeD, since the displays had differing sizes, resolutions and color reproduction. Thus, the typical emerging workflow involved trying out different settings. One possible solution for this would be placing the preview on the wall.

For both map tasks, gaze direction became important: S1 and S2 commented that gaze switches were an issue for the *SleeD-Detail* task, and this was easily visible in the videos as well. In the *SleeDOverview* task, participants needed to look at the SleeD to set the initial touch point, then switch their gaze to the wall to fine-tune the touch location to get optimal performance. Instead, several participants continued looking at the SleeD for some time.

Hence, we concur with Rashid et al. [24] that issues of perceptual transition need to be considered: Different sizes, pixel densities and color reproduction of the displays, gaze shifts and the changing orientation of the SleeD with respect to the wall all need to be accounted for when designing user interfaces for this combination of devices. This is clearly an area that warrants further investigation.

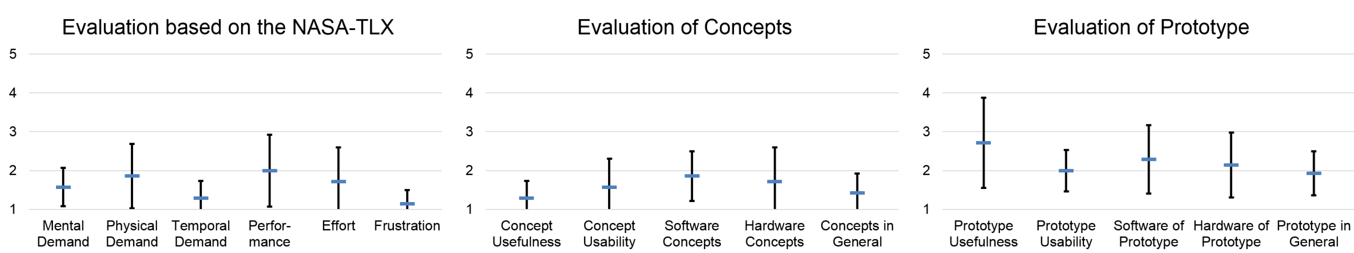

Figure 13. Results of the questionnaire. The plots show the average value per question, with whiskers showing the standard deviation. Possible answers ranged from 1 (”very good” or ”very low” in case of workload) to 5 (”very bad” or ”very high” in case of workload).

Physical Considerations

In spite of the positive quantitative rating for physical demands, fatigue due to the prototype's weight was mentioned several times as a potential problem in case of prolonged usage. This was most noticeable in the *SleeDDetail* tasks when the SleeD was mounted on the arm touching the wall (close coupling) and may have been a consequence of the high weight (133 g) of the cellphone-based prototype.

S4 and S5 mentioned that the SleeD is hard to use for very high or low wall positions, because the display orientation changes with the arm position. However, the participants were picking up and releasing photos over the complete height of the wall (from 40 cm to 250 cm) and we believe that wall interaction in general should be restricted to more accommodating heights. Furthermore, a SleeD that actually encircles the arm has more visible regions and thus will support more arm positions.

DISCUSSION

The study strongly suggests that the concepts used are sound. We investigated a diverse selection of interaction techniques and application areas, showing that the general idea is versatile and widely applicable. Importantly, nearly all study participants asked for more features, e.g., pinch to zoom in the map application, erasers and an eye dropper to choose color in the drawing application. We believe this is a very positive sign, since it shows that the concepts were clear to them and they were envisioning actual usage. Furthermore, it points to the possibility of creating complete coherent application user interfaces using this hardware combination.

Unfortunately, the current state of hardware development prevents a study with the envisioned hardware. Accordingly, we could not test features that depend on a larger, curved display, among them rotating menus and interaction on the posterior of the arm. However, we could test most concepts individually and in combination in our study. Furthermore, the study results point to several shortcomings of the current prototype that a full SleeD will likely solve. Among these are the weight of the device (leading to fatigue) as well as the smaller, flat display that impedes interaction on the device itself and is only visible in certain arm positions.

Concerning practical realization, the emergence of flexible OLED display prototypes makes it likely that the hardware restrictions of the current prototypes will be lifted in the foreseeable future. OLEDs need no backlight; the corresponding lower weight should alleviate the issues with physical fatigue. In addition, user ID recognition for multi-device systems has been demonstrated in numerous varieties. Of the proposed techniques, the IdWristbands [19] promise to be the easiest to integrate into our setup: The SleeD just needs to be able to pulse an infrared LED in the direction of the wall. Fiberio [13] points to a solution that can become commercially viable in the long term.

SleeD also has multiple benefits in comparison to concepts based on hand-held devices. Many of our techniques leverage the fact that the mobile device's display is visible and can be interacted with in close coupling situations. This applies to context-sensitive menus, seamless interaction including the drop zone and the flow concept, personal views, precision input and probing. We believe that combined with effortless switching to bimanual interaction with the wall (or with other objects such as pen and paper), this points towards powerful and truly seamless interaction using both devices.

CONCLUSION

In this paper we presented SleeD, a novel approach that combines arm-mounted touch devices with large interactive display walls. We contributed the SleeD concept, including physical considerations, an analysis of the forms of coupling between the wearable and the wall, and a diverse range of user interface techniques. Our iterative design process also yielded two hardware prototypes based on a bendable e-Ink display and a conventional smartphone. The presented sample applications further illustrate our concepts and underline the envisioned usage of this type of future devices.

Finally, we also reported on an observational user study that covers a broad range of the envisioned interaction. The valuable feedback that we received shows the high potential and broad applicability of our proposed concepts – as well as pointing towards future work in the area. This includes quantitative studies on individual techniques and a study of multi-user interaction. Furthermore, a true curved, high-performance SleeD prototype is an important piece of future work when the hardware reaches maturity.

ACKNOWLEDGEMENTS

This work was funded in part by the German Research Foundation (DFG) through the project IPAR (DA 1319/2-1). We would like to thank Plastic Logic for supporting the development of Prototype I and André Viergutz for his support.

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