Curve: Revisiting the Digital Desk

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ABSTRACT

Current desktop workspace environments consist of a vertical area (e.g., a screen with a virtual desktop) and a horizontal area (e.g., the physical desk). Daily working activities benefit from different intrinsic properties of both of these areas. However, both areas are distinct from each other, making data exchange between them cumbersome. Therefore, we present Curve, a novel interactive desktop environment, which combines advantages of vertical and horizontal working areas using a continous curved connection. This connection offers new ways of direct multi-touch interaction and new ways of information visualization. We describe our basic design, the ergonomic adaptions we made, and discuss technical challenges we met and expect to meet while building and configuring the system.

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation:
User Interfaces - Input Devices and Strategies

General Terms

Design, Human Factors

Author Keywords

curve, digital desks, direct-touch, ergonomics, interactive surfaces, workplace, tabletop interfaces

INTRODUCTION

In 1991, Pierre Wellner presented the DigitalDesk, a digitally augmented office desk [30]. The DigitalDesk can track a user's hands and paper documents using an overhead camera. A ceiling-mounted projector displays a digital desktop onto the physical desktop. Wellner's work coined the concept of digital desks that would support office workers in their daily routines.

Given that a significant part of everyday office work happens at a desk and involves a computer, integrating the computer desktop into the physical desktop seems like an idea worth further investigation. Regular office applications such as word processors or spreadsheets are currently the most important tools within professional computer use. Thus, improving computer workplaces can have a significant impact on a very large number of users. To our knowledge, little research has happened on the use of digital desks for office tasks.

Figure 1. ***Curve*** **is a digital desk concept that blends a horizontal and a vertical interactive surface. Its design takes into account existing ergonomics research and own experimental findings.**

With interactive surfaces becoming more and more ubiquitous, we propose revisiting the idea of the digital desk. Current office workplaces are hybrid environments, combining a physical desktop with a paper-based workflow and a virtual desktop within the computer screen. The horizontal desktop is suited for placing, sorting or annotating documents. The vertical computer screen is suited for reading text, viewing digital media, and editing text using a keyboard. Even acknowledging that there might never be a 'paperless office', the gap between physical and digital documents is wider than it needs to be. Our *Curve* concept (Figure 1) removes the gap between the physical desktop and the computer screen by blending both into one large interactive surface. The contributions we describe in the following are a review of ergonomic requirements for digital desks, a set of design guidelines, a detailed concept for digital desks that takes these guidelines into account, and findings from a study determining important parameters of this concept.

As this paper focuses on design and construction of digital desks, we will only briefly discuss interaction techniques for such systems in the final section.

NordiCHI 2010, October 1620, 2010, Reykjavik, Iceland.

ERGONOMICS OF INTERACTIVE SURFACES

Since, to our knowledge, little research on ergonomics for large interactive surfaces or digital desks has been published so far, we summarize empirical findings from two related fields of research: Visual ergonomics – how should a surface be designed to ease reading text and watching visual content. Touch ergonomics – which parameters influence direct-touch interaction on interactive surfaces. Finally, we condense these findings into guidelines for designing interactive surfaces for single-user workplace scenarios.

Visual Ergonomics

Several studies have explored the factors that determine how well people can view content on a screen. Mostly, these studies concerned reading tasks.

Display Properties: While basic display properties such as resolution and contrast are an important factor for visual performance and fatigue, results from empirical studies are very heterogenous and mostly cover reading text on low-resolution CRT monitors. Dillon [7] reviews empirical literature on visual ergonomics for reading tasks (up to 1992). He concludes that most studies do not provide ecological validity and results are not comparable. Ziefle's review [33] of scientific research and ergonomics standards shows greatly differing minimal, maximal, and optimal values for screen resolution and contrast, with studies contradicting each other. Ziefle [34] conducted two studies on reading performance for different screen resolutions. A screen with a resolution of 120 ppi – the highest one that was tested – performs significantly worse than paper for reading tasks. From these studies, it can be concluded that display resolutions lower than 120 ppi have some adverse effect on reading tasks compared to paper. However, there is not enough data on higher display resolutions. The aforementioned reviews suggest that displays need a resolution equivalent to printed text (300 dpi) in order to achieve a reading performance comparable to paper.

Perpendicular View: Beringer et al. [4] and Sears [23] document a *touch bias* – a constant offset between intended touch position and absolute touch position when a user's line of sight is not perpendicular to the screen. Shupp et al. [26] compared users' perfomance in visual search tasks using two different multi-monitor layouts. They found a setup that is curved around the user to be more suitable for such tasks than a flat one. Oetjen and Ziefle [17] report that reading performance degrades greatly when viewing LCD displays off-axis.

Monitor Placement: Psihogios et al. conducted a literature review and a field study investigating effects of monitor placement on visual and musculoskeletal strain [19]. Both study and review strongly suggest that a line of sight about 9-10 ° below horizontal offers the best tradeoff between visual and musculoskeletal strain. Preferences among users vary, however by approx. $\pm 5°$. Users preferred a viewing distance between 55 and 60 cm.

Viewing Distance: Dillon [7] suggests a viewing distance of a least 60 cm and regular, short breaks when working in front of a computer screen. It is widely assumed that focusing at distant objects from time to time helps to reduce visual fatigue [8]. At a viewing distance of 60 cm, and assuming an angular resolution of 0.02 ° for the human eye, a display resolution of 120 ppi would be sufficient. For a viewing distance of 30 cm - an informally estimated comfortable distance for reading a document lying on the desk - a display resolution of 240 ppi would be needed.

Suitability for different tasks: O'Hara and Sellen [18] compared reading from paper to reading from a computer screen. Based on their findings, they suggest to enhance support for three actions commonly associated with screen-based reading: annotations, navigation within the document, and spatial layout of documents. Revisiting O'Hara and Sellen's study, Morris et al. conducted a quantitative study comparing the usefulness of digital tablets, paper, horizontal and vertical displays for reading, writing, annotating and note-taking [15]. They found that participants absolutely preferred the vertical surface for writing using a keyboard. However, the vertical surface was strongly disliked for the other tasks. Accordingly, participants preferred the horizontal media (display, tablet, and paper) for annotating documents. For navigating within long documents, participants liked direct-touch scrolling on the tablet. Paper documents were not considered better suited. However, participants generally had trouble continuously adjusting window sizes and positions. They avoided placing windows across screen boundaries. One third of the participants rotated the two displays of the dual-screen setup to form a V-like arrangement, both screens facing them. Most participants also adjusted screen angles. Morris et al. derived a number of suggestions for systems supporting digital reading tasks: (1) Horizontal and vertical displays should be combined as they uniquely cater to different tasks. (2) Systems should support bi-manual interaction for navigating within documents. (3) Users should be able to adjust displays to their preferences. (4) Multiple input devices such as keyboard, mouse, pen, and direct-touch should be supported as each offers unique advantages for certain tasks. (5) Window management should better support navigation in and manipulation of digital documents.

Touch Ergonomics

Touchscreen pointing performance has been the subject of scientific research for several decades. Most studies concern target selection tasks.

Direct-Touch Advantages: Several comparative studies on mouse input, single-touch and multi-touch input have been carried out [11, 13, 24]. They show that direct-touch is superior to other input methods under certain conditions (e.g., relatively large targets), and that direct-touch interaction is very well-suited for bi-manual input. For certain tasks, mouse input is superior, however.

Size: In a limited, only partially published study, Elliott and Hearst [9] analyzed how the size of an interactive surface affected a sorting task. The GUI was always scaled to the whole surface. Participants found a desktop-sized surface to be too large, as screen contents were placed in the participants' peripheral viewing area. A tablet-sized touchscreen was deemed to small by most users. No quantitative results were reported.

Placement: Morris et al. conducted a field study on usage patterns for touch-sensitive displays that could be placed on a desk horizontally or vertically [14]. Users preferred vertical placement next to the existing screen. Users tilted the display towards them in horizontal position by putting objects under one edge. This was reportedly done in order to reduce glare from overhead lights and to improve the viewing angle. Repeatedly, users found the horizontal display to be in their way, taking up desktop space that was used for arms, keyboard, and mouse.

Angle: Sears [23] reports on study that found that sitting users preferred interacting with touchscreens tilted 30 ° towards them from the horizontal. This angle was also the least fatiguing. No distance between user and touchscreen is given. Users rested their elbows on the desk for conditions where this was possible. Ahlström et al. [1] confirm this preferred angle for a small touchscreen that is placed 0.3 m from the desk's front edge. They add that absolutely horizontal or vertical positions were rated the worst by participants. Resting the elbow on the desk reduced the perceived fatigue. Both studies did neither control nor measure participants' height or arm length, however. Additionally, in both studies the touchscreen's center was at a different height for each tested angle. Therefore, the absolute value of 30 ° should be taken with care. Both studies only investigated single-touch tapping. Schultz et al. [21] describe a thorough study on the best placement of touch screens for standing users of different height. They conclude that there is no single "best" angle or position. Instead, the optimal parameters vary greatly between users. Overall, there is no convincing estimate of an ergonomically good display orientation for direct-touch interaction.

Survey of Early Adopters: Benko et al. conducted a survey of 58 researchers, developers and designers of interactive surface systems [3]. As interactive surfaces were not widely used in 2007, those early adopters are argued to be the best source of information about usage habits. Approximately one third of respondents uses interactive surfaces several times a day, another third uses them at most once a month. A typical session lasts between 15 minutes and 1 hour. Only 5 percent of respondents use these systems for typical productivity tasks – only one person uses one as primary workstation. Desired features for long-term single-user systems are: direct-touch interaction, multi-touch support, a large display space, support for standard applications (also mentioned by [25]), and support for standard input devices The primary reason why respondents would not want to use a horizontal display for longer sessions was neck and back strain. Several respondents highlighted the need for an adjustable surface.

Long-term Use: Wigdor et al. report on one person using a DiamondTouch interactive surface as his primary workstation over the course of 13 months [32]. Privacy was an issue, as a passer-by could easily read the large screen's content. As the user wanted to also use the DiamondTouch as a regular table, the surface was only slightly tilted towards him. Tilting was considered beneficial for the user reaching the distant corners. It also improved the viewing angle. The user strongly suggested using a real keyboard instead of the on-screen keyboard. Contrary to reports from short-term studies, the user did not experience arm fatigue. This might suggest that training can mitigate the effect.

Design Guidelines Derived From the Literature

The research presented above provides strong foundations for a number of design guidelines regarding digital desks. The following guidelines are purely based on the aforementioned studies and interviews. It should be noted that most studies focused on reading and target selection tasks. While these are probably representative of many real-world tasks, they do not exactly mirror everyday computer use. This means that there might be additional ergonomic requirements that only become apparent in certain scenarios. It does not limit the validity of the following guidelines.

Provide Ample Resolution

Display resolution should be as high as possible. For reading tasks a physical resolution of at least 120 to 240 ppi should be offered [7, 33, 34]. For everyday use, the display resolution needs to be at least as high as on a standard computer screen: about 90 ppi.[1]

Maximize Screen Real Estate

Users prefer large interactive surfaces [3]. Even areas outside of the primary interaction space are used for laying out multiple objects spatially [10, 18]. No study so far found that users were overwhelmed by too large interactive surfaces. Therefore, a digital desktop should be at least as wide as a user can reach with her hands.

Allow Direct-Touch Interaction Across the Whole Display

Direct-Touch interaction is faster than mouse input for many selection tasks [11, 13, 24]. Users want direct-touch interaction [3]. As interaction patterns and spatial layout of digital documents are user-specific and change often [15], direct-touch interaction should be possible across the whole display area.

Offer Both Horizontal and Vertical Surfaces

Depending on the task at hand, users prefer horizontal or vertical surfaces. For reading tasks a nearly vertical display is more suitable while users prefer a horizontal surface for annotating and navigating digital and physical documents [3, 4, 15, 23]. Therefore, a digital desk should offer both a a more or less horizontal and a more or less vertical interactive surface.

Support Dual-Use

As a digital desk replaces the wooden desk, it needs to offer the same advantages. Users should be able to place books, papers, personal gadgets, coffee cups, and pizza on the digital desk. Ideally, a digital desk should offer about the same area for dual-use as the wooden desk [32].

Support Alternative Input Devices

Researchers agree that different input modalities like mouse, pen, and direct-touch complement each other. It has been

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[1] For a display surface of 61 cm by 46 cm (Microsoft Surface), this means a physical resolution of 2160x1630 pixels. In order to achieve a paper-like resolution of 300 ppi, a physical resolution of 7200x5400 pixels would be required.

suggested that interactive surfaces should also support alternative input devices [3, 15, 32]. This is especially true for digital desks where a user might navigate a directory tree using the mouse, drag a document towards himself with his finger, annotate it using a pen, and extend it using a keyboard. Therefore, digital desks should support a multitude of input devices that offer ergonomic advantages for certain common tasks. Keyboard, mouse, pen, and multi-touch are essential.

Reduce Visual and Musculoskeletal Strain

As digital desks will be used for long periods, they should take into account basic workplace ergonomics. Desk design should reduce both visual and musculoskeletal strain. Therefore, we suggest to take into account the following recommendations: Of course, the desk should generally conform to established ergonomic guidelines. The line-of-sight should be perpendicular to display [4] and be inclined about 10 ° downwards from the horizontal [19]. The distance between the user and the display should be at least 60 cm [8, 19]. The design should offer support for regular short breaks [8]. Users should be able to easily reach all areas of the interactive surface with their hands [32]. They should be able to rest their arms and elbows on the desk to stabilize and ease touch interaction [1, 23].

Allow Users to Adjust Parameters

There is no 'standard user'. Ergonomic requirements between different users vary greatly. Therefore, as many physical parameters of the interactive surface as possible should be adjustable. This includes viewing angle, touch angle, and position [14, 15, 21].

Scope of these Guidelines

These eight guidelines should be taken into account when designing digital desks and other interactive surfaces for long term use. They are not specific to single-user workspaces. We acknowledge that some guidelines are hard to meet with currently available hardware (e.g., full adjustability), and others conflict with each other (e.g., size vs. resolution). Therefore, tradeoffs have to be made in some cases. Nevertheless, we see these guidelines as sensible goals. In addition to these ergonomic guidelines, several other guidelines can be derived from the presented works. For example, it seems necessary for digital desks to also support standard (or *legacy*) applications like word processors or spreadsheet applications. As these do not directly inform the physical design of digital desks, we do not discuss them in this paper.

DIGITAL DESKS

Several researchers and designers have explored how physical desktops can be used as an input and display area for human-computer interaction. In the following, we give an overview of the research on digital desks and discuss how the aforementioned design guidelines have been taken into account. While a multitude of research prototypes make use of a digitally augmented desk or table, very few look at digital desks for traditional office work.

In 1991, Pierre Wellner presented the DigitalDesk [30], a physical desktop onto which a ceiling-mounted projector projected a graphical user interface (GUI). A computer-controlled camera captured hand gestures on and above the desk. Users could interact with the system by directly touching GUI elements, and merge or exchange data between paper-based and digital representations. Apart from some anecdotal user feedback ("much more healthy than a screen") [16], Wellner did not discuss ergonomics in any of his papers on this topic [16, 30, 31].

In 1994, Bruce Tognazzini produced "Starfire", a futuristic concept video for Sun Microsystems, visualizing novel ways of HCI in office settings [27]. A central part of the proposed scenario is a digital desk incorporating a large vertical display which is curved around the user (Figure 2). In the video, the horizontal desk is used for reading and annotating digital documents while the vertical part is used for videoconferences. Direct-touch interaction on the vertical part is just shown in one scene when the user drags an image from the horizontal to the vertical display part.

Figure 2. The digital desk shown in Tognazzini's *Starfire* concept video from 1994 offers a horizontal and a vertical interactive surface [27].

In 1998 Raskar et al. [20] presented an early idea to create a more digital office for everyday work. They used projections to create display space on white walls beyond a desk. They assume that large screens offer a more immersive way of remote collaboration, which is useful for everyday work with remote collaboration partners. As mentioned before, in 2007 Wigdor et al. report findings of a long-term study, where one employee used a DiamondTouch desk as his primary workstation over the course of 13 months [32]. Commercial office applications ran on a standard operating system (Windows XP). Instead of keyboard and mouse, the person used the on-screen keyboard and direct-touch interaction.

In 2007 Microsoft presented DigiDesk, a concept for a knowledge worker's workplace. It consists of a slightly tilted MS Surface with an additional vertical display along its longer side, which is not touch-sensitive. DigiDesk has only been shown at trade shows and there was no mention of it after 2007. In 2009, Weiss et al. presented a poster on BendDesk [29], a digital desk concept that combines a horizontal and a vertical interactive surface, connecting them with a curved segment[2]. BendDesk has the same two drawbacks as the

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[2] A poster on our Curve concept has been presented at the same conference. Neither group was previously aware of each other's work in this direction.

Starfire digital desk: a user can not look over the top edge, and the absolutely vertical surface makes direct-touch interaction fatiguing. We discuss these issues in more detail in the following section.

Other research projects dealing with non-planar interactive surfaces, as summarized by Benko et al. [2], are not related to desks and do not take ergonomic guidelines into account. Beside these research projects there are some commercial or art projects dealing with different levels of interactivity, display size, and usage scenarios. To our knowledge none of them have considered ergonomic issues.

BLENDING HORIZONTAL AND VERTICAL SURFACES

Given the lack of ergonomically grounded digital desk designs, we propose Curve, an improved shape for digital desks. Curve takes into account the presented ergonomic requirements and offers novel interaction possibilities. The Curve desktop consists of a horizontal and a vertical interactive surface, seamlessly connected by a curved segment (Figure 3, right). In the following we describe the concept behind Curve and the design decisions we made.

General Concept

As proposed in our guidelines, a digital desk should offer both a horizontal and a (nearly) vertical interactive surface. While such a desk could just use one continuously tiltable desktop, this would require users to readjust the desktop every time they switch tasks. Offering both a horizontal and nearly vertical interactive surface allows the user to choose the one that is better suited for a specific task. Switching can be done on-the-fly. We argue that it is not enough to just place two touchscreens end-to-end. Instead, there should be a seamless, continuous transition between horizontal and vertical area. This blending surface – the curve – acts as a gateway between both and as an interaction area with unique properties. As such a continuous transition is technically much harder to achieve than a hard edge between both surfaces, we describe our rationale in the following.

Continuity

While related work has shown that combinations of horizontal and vertical interactive surfaces can provide ergonomic benefits, the question remains how to combine those surfaces. Standard multi-display setups position screens right next to each other. The interior screen bezels pose a border between display areas, dividing them visually and disallowing direct-touch drag-and-drop operations across screen boundaries. Bi et al. [5] have shown detrimental effects of interior bezels on both visual and interactive tasks. Eliminating the bezels still has the drawback that horizontal and vertical surface would touch at a steep angle. We propose softly blending both surfaces using a curved segment inbetween. This would result in a seamless, continuous interactive surface. Such a design provides better visual, haptic, and mental continuity than the other two designs mentioned before. (Figure 3).

Visual Continuity. A continuous display space seems advantageous over one that is divided by screen bezels or hard edges. Users of multi-monitor workstations avoid spanning windows across multiple screens, as the screen bezels create a visual discontinuity[15]. Even without bezels, hard edges between adjacent display surfaces introduce kinks within objects crossing the edges. Continuously blending both surfaces avoids such kinks. Ware et al. [28] have shown that smoothly continuous lines are perceived more quickly than kinked lines.

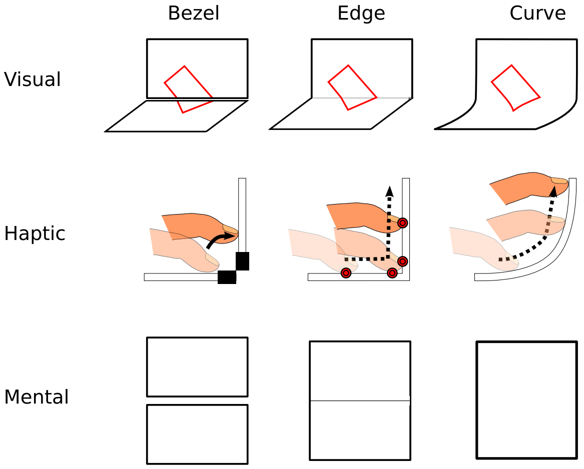

Figure 3. A continuous interactive surface (right) avoids the visual, haptic, and conceptual problems that are present in surface combinations with a bezel (left) and/or hard edge (middle) between horizontal and vertical surface.

Haptic Continuity. For direct-touch interfaces, haptic continuity is as important as visual continuity. Bezels between interactive surfaces require the user to lift her finger at the edges and reposition it on the adjacent surface. This makes continuous drag-and-drop operations impossible. On a bezelless setup a finger at the edge between two surfaces touches both simultaneously with different areas of the finger tip, leading to tracking errors. Additionally, the hard edge forces the user to touch with her finger tip instead of the finger pad when interacting in the lower part of the vertical surface. The user has to adjust her movements as she now uses a different part of her finger for pointing. Pressing the finger tip against the vertical surface would be more straining, too. A curved transition between both surfaces effectively eliminates these problems.

Mental Continuity. We argue that the way the user experiences the surface both visually and haptically influences her mental model of the surface. Bezels strongly suggest to the user, that objects should be on only one surface, not crossing boundaries [15]. The visual and haptic qualities of hard edges discourage placing objects on the edge, and dragging objects across this edge. While the surfaces appear directly adjacent, they are still divided. The curved surface dissolves the difference between horizontal and vertical surface, uniting them.

Partial Planarity vs. Continuous Curvature

The final Curve concept is relatively conservative, seeing the curved area primarily as a necessary connection between horizontal and vertical segment, not as a feature on its own.

Two other designs were considered and rejected: (1) a continuously curved, *C-shaped*, segment instead of the vertical segment, and (2) a surface that is also curved horizontally. Completely curving the vertical segment would make it easier to reach the top corners as they would be bent towards the user. Additionally, the distance between eye and surface could remain constant, avoiding focus changes. However, there are several drawbacks to such a design: It is not clear, whether the center of the curved segment should be the user's eyes or his shoulder joint. More important, humans are accustomed to viewing perspectively distorted flat surfaces, like books or computer screens. Viewing non-planar distorted images – as it would happen within the curve – increases visual processing load [28]. This would mean constant readjustment when alternately viewing flat physical documents and curved virtual documents. The constant viewing distance might also cause eye fatigue. Direct-touch interaction near the top would become harder, as the finger can no longer rest on an inclined surface. Another approach would be to horizontally curve the surface similar to the Starfire desk. This would allow the user to comfortably reach every part of the surface, as well as offer a perpendicular viewing angle across the whole surface. However, the aforementioned issues also apply here. The constant viewing distance would also increase eye fatigue. The non-planar distortion of images increases visual processing load. As there would be only one optimal seating position, the user can not move left or right. A second user would have a significantly different view than the first user. Being off-center, she would also have problems reaching the whole surface. A horizontally curved surface might also cause the user to feel enclosed by her desk. For these reasons, we think that the curved segment should be as small as ergonomically sensible. This is realized in our design.

DESIGNING THE SHAPE

The aforementioned guidelines and ergonomics standards provide a reliable basis for designing a digital desk like Curve. However, several concrete design decisions are not covered by these guidelines. Thus, the next step is to determine an 'optimal' shape for the prototype. Our goal in this case is not to design the ultimate digital desk, but to develop a functional prototype that can be used to verify our assumptions, advance our insight into the different properties of the segments, and investigate novel interaction techniques for digital desks. Therefore, we define 'optimal' as being as usable as possible for as many users as possible. Additionally, we need to build the prototype using currently available materials. In this section we describe which parameters can be adjusted in our concept and which combination of parameter values best fits an 'average user'. To this end, we conducted a user study with an adjustable paper prototype.

Designing for the Average User

An important finding in previous studies on visual and touch ergonomics is that users prefer to adjust several parameters of their screen, such as the inclination angle or multi-monitor arrangements. However, current technology does not allow for complete adjustability unless other important requirements are forfeited. For example, the current state-of-the-art method for implementing large interactive surfaces are back-projected screens. However, a back-projected surface must have its supporting material on its edges only, requiring a rigid structure of the surface itself. This in turn means that the surface cannot be easily bent or stretched. Acknowledging this current limitation, we decided to design our first prototype for an 'average user' to meet the requirements of a large user group as close as possible. The anatomy of this average user is based on DIN 33402-2[6], a standard documenting average anatomical measures for German adults[3].

Determining Parameters and Values

We were able to integrate some of the aforementioned recommendations into our design. However, to our knowledge, recommendations for non-planar displays do not exist in terms of the screen's height, its curve radius, and the backward inclination of its vertical part. Nevertheless, these properties cannot be adjusted later. Thus, we conducted an experimental evaluation with the goal of identifying sensible average values for these parameters. To do so, we collected qualitative user preferences within the context of direct-touch interaction tasks. We settled on evaluating three different curve radii, three different inclinations of the vertical segment, and two different heights. As the parameters are interdependent, we had to evaluate 18 ($3 \times 3 \times 2$) combinations.

Inclination of the vertical segment. As mentioned above, a gaze inclination of about 10 ° from the horizontal minimizes visual and muscoloskeletal strain. In order to allow for a line of sight perpendicular to the vertical segment's surface, the segment should be inclined backwards by about 10 °, too. We assumed that a greater inclincation might better support fingers and hands when interacting on the vertical segment. However, the more the vertical part is inclined the less reachable are the upper parts of the display. We found that 15 ° should be the maximum inclination of the display. Therefore, we chose to compare inclinations of 5 °, 10 °, and 15 °.

Curve radius. The curved part serves as a connection between the vertical and the horizontal part in terms of both input and output. While visual continuity is not affected by the radius (assuming that the radius is larger than 0 cm), we were more concerned of potential direct-touch operations in this area. Especially dragging operations might be influenced by the curve radius. A smaller radius approximates a corner and would thus not be beneficial (see Figure 3). Larger radii allow for smoother transitions between both surfaces but take away area from the horizontal and vertical segments. Thus, we chose to compare curve radii of 5 cm, 10 cm, and 15 cm.

Display height. Based on recommendations for standard desks in office spaces, we used a desk height of 72 cm. To evaluate potential "boxing effects" (i.e., the user feeling to be enclosed by the display), we compared two different heights for the vertical segment. These heights were determined by an average user's eye level in a seated position: 120.75 cm above ground [6]. We chose to compare a top border 5 cm below eye level to one 5 cm above eye level. This lead to a height of 43.75 cm, respectively 53,75 cm,

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[3] There is very little difference between the anatomical measurements of an average German, an average European, and an average American. As our study participants were and will be Germans, we used the German values.

above the desktop.

Tasks

During the study, users had to trace several (differently colored) paths on each setup with their fingers. Participants were allowed to choose which finger (and hand respectively) to use. However, some paths had to be traced simultaneously using two fingers (and hands respectively) to simulate multi-touch gestures. The paths were chosen to test (1) the reachability of the display's edges and (2) the radius of the curve by going from the horizontal to the vertical part and vice versa. Figure 4 shows the arrangement of the paths on one of the prototypes.

Figure 4. Arrangement of the paths on one of the paper screens. Probands of the user study had to draw this paths with one or two fingers. This task had to be performed on each of 18 prototypes. ***Traces enhanced for print.***

Each task was kept short in order to reduce the risk of fatigue within one setup. Participants were allowed to decide about the order in which they wanted to trace the paths. We asked our participants to think aloud while tracing each path. After they completed one setup (i.e., one combination of the mentioned parameters), they had to fill out a questionnaire asking them about their subjective rating regarding the previous prototype. After they completed the whole study, they had to rank their three favored ones again. These were determined by evaluating the ratings for each individual prototype.

Apparatus

To simulate our envisioned, curved display we built an adjustable paper prototype as shown in Figure 4. Inclination, curve radius, and height could be changed independently by moving the upper fixture or exchanging parts of the side fixtures. To avoid any bias during the study, participants had to leave the room when the prototype was readjusted for a set of different parameters. Therefore, participants were not aware of the changes made to the prototype.

Participants

We recruited nine participants for our study (four female), ranging in age from 22 to 27. A tenth person only participated in a pilot study a priori to the actual experiment. The main consideration in choosing the participants was their body height. Out of the nine participants, three were considered *short* (< 165 cm), three were *mid-size* (165 cm – 175 cm), and three were *tall* (> 175 cm) [6].

Measuring User Preferences

As we favored subjective, qualitative ratings over task time and error rate, we asked the participants to rate and to rank the prototypes. One possible way to do so would be to rank the prototypes according to their average rating. However, such rankings by points have various limitations. For example, bias effects may disproportionally influence the outcome. Therefore, we used the Schulze method as a widespread Condorcet method to calculate a "winning" shape using pair-wise comparisons [22]. For practical reasons, each participant first had to rate every of the 18 setups. After the study, he or she got to test the three best-rated setups again and had to rank them from one to three. In addition to a questionnaire, we also analyzed videos recorded with two cameras to identify verbal statements and observe physical specifics of participants.

Findings

Nine of the ten highest rated setups had the lower height of 43.75 cm. These setups with the lower screen height scored 75.44 points compared to 66.16 points for the setups with higher screens (Figure 5a). Most interestingly, a large number of users stated that they mainly rejected the higher screen due to difficulties reaching the top regions. Although we assumed that the larger prototype would result in a feeling of enclosure, participants stated that the height would be less important once direct interaction with the top regions is not necessary. Overall, the lower height was clearly preferred, though.

In terms of the inclination of the upper segment of the display, we found that 5° was favored the least with an average score of 69.22. However, the remaining two inclinations (i.e., 10° and 15°) were ranked equally with 71.7 (10°) and 71.48 (15°). Since the results regarding the height of the display (i.e., $43.75cm$), we further evaluated the score for the lower displays only. There we found that the inclination of 15° was preferred (78.11) over 5° (72.92) and 10° (75.29). Furthermore, we found that this inclination was present in the two top-ranked display configurations with an average of 78.72 (Figure 5d). The third property we evaluated was the radius of the curve connecting both segments. Here we found that a radius of $5cm$ is less preferred (68.57) than $10cm$ (71.56) and $15cm$ (72.26). These results are comparable to the ones for the lower vertical segment only. The largest radius is still slightly preferred over $10cm$ (77.26 versus 76.55) while the small radius again is rated the worst (72.52) (Figure 5c).

An interesting side-effect we discovered was that participants perceived a change in the display's width between different setups. However, we did not change this parameter. In general, 88.8% claimed that the display was wide enough (i.e., not too narrow). Regarding whether the display was too wide, no tendency could be observed. Furthermore, we asked participants to rank their individual top three setups and used OpenSTV[4] for calculating the winner using the

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[4] `http://www.openstv.org/`

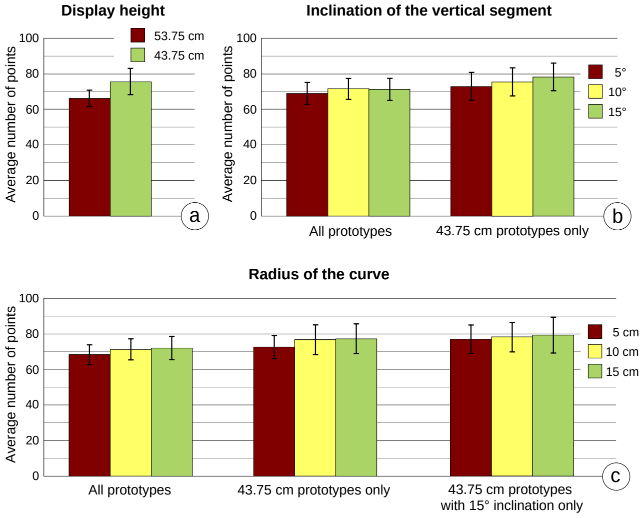

Figure 5. User preferences for certain shape properties. Users strongly preferred the lower height (a) and generally preferred a greater inclination of the vertical part.

Schulze method. We were able to identify two winners (only with slight advantages) with the same height ($43.75cm$) and inclination ($15\,^{\circ}$) while differing in the radius ($10cm$ versus $15cm$).

Final Properties

Considering the related work, our design guidelines, and the findings from our study, we arrived at the following combination of design parameters for our prototype (Figure 6).

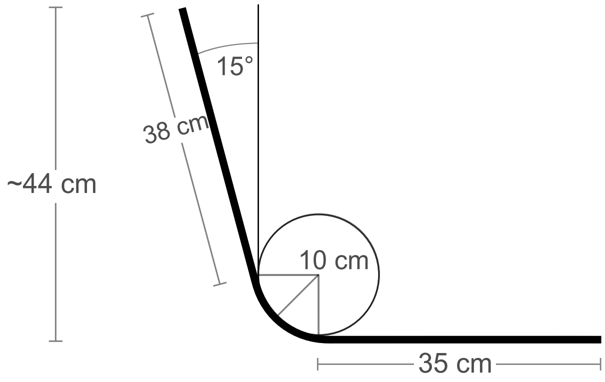

Figure 6. Final panel dimensions according to user study. The height of the vertical segment was set to 44cm, the radius to 15 ° and the curve radius to 10cm according to the results of our user study.

Vertical Segment. The ”vertical” segment is tilted backwards by 15 °. This reduces strain on finger and hand, as the finger can rest on the surface. For precise finger input, the user can rest the whole hand on the surface. On a completely vertical surface, the user would need to press his finger against it the whole time. The average user is able to reach all screen areas without moving on the seat. Given an ergonomical head inclination of 10 °, the user's line of view is nearly perpendicular to the surface [19]. The distance between eyes and surface is 60 to 70 cm, the minimum viewing distance for long-time reading tasks [8]. The top edge of the vertical surface is 44 cm above the horizontal surface and 5 cm below the average user's eye level, allowing her to easily avert her view from the screen. This allows her to re-focus at distant objects from time to time, reducing visual strain. Additionally, she can see and communicate with co-workers. This might prevent her feeling walled in or disconnected from the environment. With her head slightly inclined, the screen fills the user's whole field of view, minimizing external visual distraction.

Horizontal Segment. The horizontal segment has a depth of 35 cm. This is the maximum depth that still allows an average user to comfortably reach the whole vertical segment. The user can rest arms and hand on the horizontal segment, allowing for effortless direct-touch interaction there. Resting his elbows on the horizontal surface, the user can also comfortably reach the central part of the vertical segment. In order to retain its dual-use nature, we therefore decided to leave it in the horizontal position.

Curved Segment. The radius of the curved segment is 10 cm. We would have preferred a radius of 15 cm, as it offers a smoother transition between horizontal and vertical segment. However, a larger radius would have either reduced the horizontal surface area, or moved the vertical area farther away from the user. As the users' preference for a 15 cm radius over a 10 cm radius was only marginal, we chose the smaller radius. When resting his elbows near the front edge, the average user's fingertips touch the curve. At this position, the curve's pitch is about 30 °, the inclination suggested by e.g. by Sears [23]. The segment is curved uniformly with a constant radius.

Width. Our current *Curve* prototype is 120 cm wide. In general, the width of the desk is not constrained. However, only a limited area can be used for direct-touch interaction without moving the seat. With increasing width, the viewing angle gets worse. Therefore we chose a width that would allow the user to easily reach the whole surface with her hands. Curve is also wide enough to support two people sitting next to each other. Our study indicated that users did not see the need for a wider desk.

REALIZATION

Based on the parameters determined empirically and from related work, we implemented a functional prototype. Most hardware components and technologies we used to build Curve are well-known but were not combined the way we did, yet. In order to get a stable but also customizable case for our system, we chose wood as primary building material. To get a seamless output and to preserve the possibility to use IR-based multi-touch input we used a curved 12mm thick, acrylic panel which was manufactured by a local company. On top of the acrylic plate there is a compliant surface made of rubber latex and a Rosco Grey projection screen as the topmost layer. Though it is flexible enough to be installed on a curved surface it also seems to be quite scratch-resistent and has good projection properties. We installed two projectors (Sony VPL-HW 10), each with a resolution of 1920 x 1080 px, for back-projection on the screen. Due to the fact that there were no high resolution short throw projectors available when we built the system, we had to use mirrors.

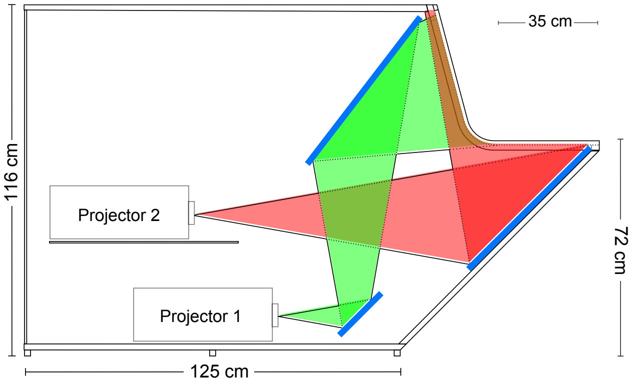

Figure 7. The wooden frame of our prototype allows for quickly modifying and extending the system. The interactive surface is made of a custom-bent, 12mm thick, acrylic plate. On top of the plate is a compliant surface made of rubber latex, and a Rosco Grey projection screen. Two HD projectors project the screen from the back. Four Point Grey FireFly MV cameras capture touch and proximity on the surface.

In order to reduce the overall length of the case we took three mirrors (first surface and foil mirrors) while still having an almost orthographic projection onto both surface areas (see 7). As we chose FTIR [12] for sensing multi-touch input, we assembled chains of SMD LEDs on the outer edge of the curved acrylic panel. For tracking touch points we use four Point Grey Research FireFly MV cameras, each with a resolution of 640 x 480 px at 60Hz. Each camera tracks a bit more than a quarter of the entire screen space without using installed mirrors. The camera images are undistorted and stitched together in software.

LIMITATIONS

In order to build Curve with currently available technology, we had to compromise in a few areas. Additionally, we had to balance contradicting requirements. In the following we list areas where we had to make such tradeoffs. It should be noted, that all of these tradeoffs are caused by hardware limitations, not by inherent shortcomings of the design.

Screen Size and Resolution. The current Curve prototype supports a visual resolution of 1920 x 1730 px projected by two projectors onto a 90 x 80 cm area. This results in a screen resolution of approximately 50 ppi. While a higher resolution is certainly of advantage for reading tasks, we have found it to be sufficient for many current office applications. However, it is planned to at least double the resolution of our system in the medium future.

Leg Room. In order to project on the horizontal surface at a perpendicular angle, we had to limit legroom. Especially tall users have problems fitting their legs under the desk.

Adjustability. As flexible, robust, large touchscreens will not be available in the near future, we had to use a bent acrylic plate, projecting from the back onto an attached projection screen and using FTIR for input. The rigid setup does not allow for the user to adjust properties like inclination, height, or depth of the setup.

Only Touch Sensing. The current prototype uses only FTIR for tracking touches on the surface. This setup can not detect hovering or gestures above the surface. It is also not possible to capture paper documents that are placed onto the surface. Therefore, the next steps will be to add diffused illumination (DI) and overhead cameras to our setup.

SUMMARY AND FUTURE DIRECTIONS

In this paper we have proposed a number of guidelines for the design of digital desks. These guidelines are based on a literature review on ergonomic parameters of interactive surfaces. Based on these guidelines, we have proposed Curve, a novel design for digital desks that smoothly blends a horizontal and vertical interactive surface. We have justified its properties and discussed the limitations, most importantly the lack of adjustability. Finally, we report insights gained by building a functional prototype. In our opinion, digital desks are an important and interesting research area where many questions still have to be answered or even posed. We hope to have contributed a small step into this direction by proposing a physical design for digital desks. Next, we want to look at the inherent affordances and properties of the three segments (i.e., horizontal, vertical, and curved). A first study will explore quantitative benefits of a curved connection compared to a hard edge between horizontal and vertical segment. Another interesting question is, how well the different segments are suited for different tasks like reading, annotating or sorting. An investigation into drawbacks of such large interactive surfaces seems worthwhile, too. Once the basic properties are explored in more detail, we suggest looking at specific interaction techniques that are fostered by Curve's shape. For example, the curved shape encloses an interaction space above the surface, allowing for 3D interaction. Finally, the long term goal is to explore how digital desks can support common office workflows, enhance collaboration, and make office work a whole-body experience.

ACKNOWLEDGEMENTS

We would like to thank Christian Zimmermann for providing profound critique on our initial designs, Dominikus Baur, Toni Zeitler, and Alex Lang for discussing the Curve design with us, Thomas Müllauer and the university's carpentry for building the frame of our prototype.

Study details, blueprints, and additional content available at:
http://www.curve-project.org/

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