Paddle: Highly Deformable Mobile Devices with Physical Controls

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ABSTRACT

We present the concept of highly deformable mobile devices that can be transformed into various special-purpose controls in order to bring physical controls to mobile devices. Physical controls have the advantage of exploiting people's innate abilities for manipulating physical objects in the real world. We designed and implemented a prototype, called Paddle, to demonstrate our concept. Additionally, we explore the interaction techniques enabled by this concept and conduct an in-depth study to evaluate our transformable physical controls. Our findings show that these physical controls provide several benefits over traditional touch interaction techniques commonly used on mobile devices.

Author Keywords: Deformable Interfaces; Tangible Interfaces; Mobile Devices

ACM Classification Keywords: H.5.2 [Information interfaces and presentation]: User Interfaces: Input devices and strategies

INTRODUCTION

Touch screens have been widely adopted in mobile devices. Although touch input is very flexible in that it can be used for a wide variety of applications on mobile devices, touch screens does not provide physical affordances [13], encourage eyes-free use [5] or utilize the full dexterity of our hands [18] due to the lack of physical controls. On the other hand, physical controls are often tailored to the task at hand [13], making them less flexible and therefore less suitable for general purpose use in mobile settings. In this paper, we show how to combine the flexibility of touch screens with the physical qualities that real world controls provide in a mobile context. We do so using a deformable device that can be transformed into various special-purpose physical controls. To demonstrate this concept, we present one possible implementation, called *Paddle* (Figure 1).

Researchers already explored how bending [17, 19] and folding [7, 15] interactions supported by deformable mobile devices can be used as physical controls. Compared to traditional tangibles and touch screens, however, these controls lack affordances in that it is often unclear how folds and bends map to actions [19].

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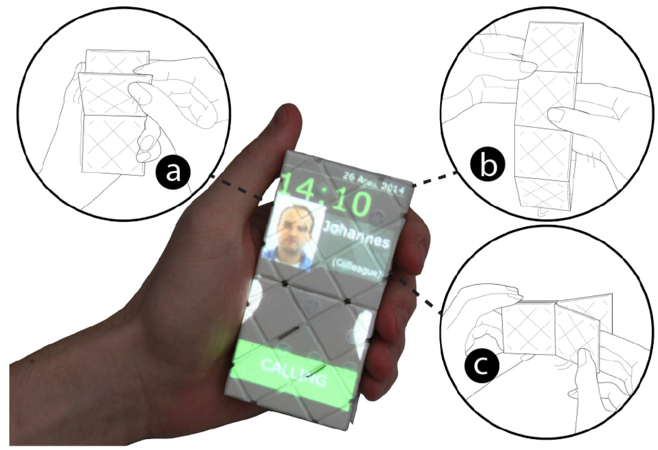

Figure 1. Paddle supports several physical controls, including (a) peeking, (b) scrolling, (c) leafing.

When the number of possible deformations a device supports increases, there is a novel opportunity to transform these devices into differently shaped physical controls that provide clear physical affordances for the task at hand. Paddle is an early prototype of such a device and allows switching between various physical controls, including a window to peek at content (Figure 1-a), a ring to scroll through lists (Figure 1-b) and a book-like form factor to leaf through pages (Figure 1-c). Similar to other prototyped deformable devices [15, 16], Paddle bridges the gap between differently shaped mobile devices, such as phones, tablets and wristbands. Paddle's ability to transform to various physical controls, however, has to our knowledge not been investigated before.

When transforming a device to differently shaped physical controls, it should be possible to switch between these shapes in only a few steps. In contrast, earlier prototypes of deformable mobile devices [7, 15, 19] are paper-like and thus support an origami transformation model that often requires numerous transformations. As Paddle is based on engineering principles used in the design of 3D puzzles, the transformation model is superior to origami and allows switching between different shapes in only a few steps (e.g. two steps to change a small flat form factor (Figure 1-a) into a ring (Figure 1-b)).

Contribution

The main contribution of this paper is the concept of *highly deformable mobile devices that can be transformed into various special-purpose physical controls to bring physical controls to mobile devices*. We demonstrate this concept using one possible prototype, which we call *Paddle*. Additionally, we explore the novel interaction techniques enabled by Paddle. Finally, we report on an in-depth study showing that physical controls supported by Paddle have several benefits compared to traditional direct touch interactions on mobile devices.

PADDLE

The mechanical construction of our prototype, Paddle, is based on principles used in the design of the Rubik's magic puzzle, a folding plate puzzle (Figure 3). Tiny infrared reflective markers are attached to this device and tracked with an optical tracking system. This enables us to project on the device to provide visual output. Similarly, touch input is enabled by tracking the fingers of the user. In the future however, we envision Paddle devices to be self-contained using electronic connectors to track the topology of the device [8] and tiny integrated displays [23], as those used in Tilt displays [1] and Facet [22], for visual output.

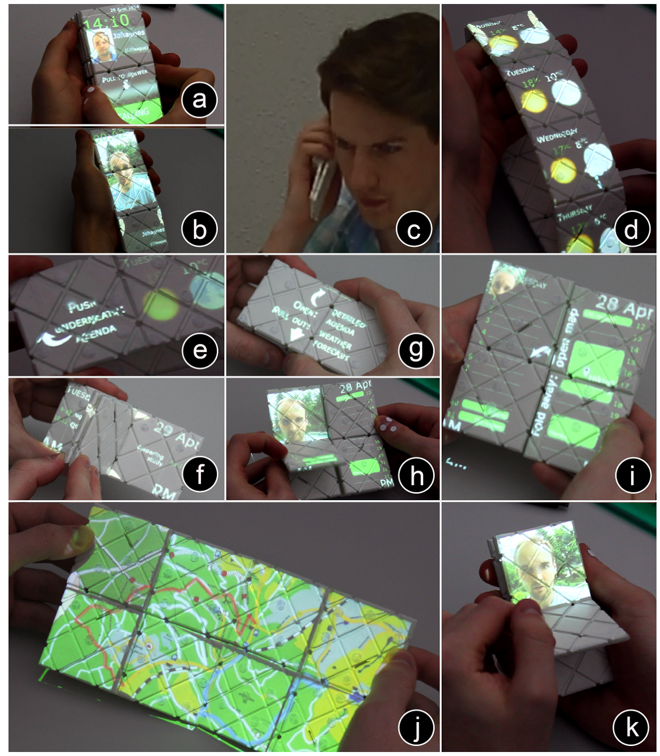

Figure 2. An example interaction that illustrates how Paddle could be used during a call.

Scenario

Figure 2 shows an example interaction that illustrates how Paddle can be used. (a) Adam gets a call from his close friend John on his Paddle, to see if he is in for a hike this week. (b-c) Adam answers the call by unfolding the compact device to a flip phone, which is more comfortable to hold while calling. (d) After a short chat Adam quickly transforms the device into a ring shape to scroll through the weather forecast of the next days. (e-f) On Wednesday and Thursday the weather looks perfect for a hike and Adam transforms the device into an agenda book through which he can leaf to see when he is available. (g) Both agree to hike on Tuesday and Adam unfolds his Paddle to see his schedule for that day. (h) Meanwhile, Adam can peek to check the status of the call or look for incoming emails. (i) Adam notices that he is only available in the afternoon and adds the appointment. (k) He unfolds his Paddle to a map on which he can plan a hike through the woods.(j) At the end of the call, John and Adam say goodbye and Adam folds his Paddle back in a compact form to fit inside his pocket.

BENEFITS AND LIMITATIONS

Highly deformable mobile devices that can be transformed into various physical controls have the following benefits compared to existing deformable devices and traditional mobile devices operated by touch:

(1) *Combining multiple special-purpose tangibles in a single mobile device.* Paddle abandons the idea of mobile devices having rigid, flat shapes with pointing as the sole interaction technique. Paddle therefore brings tangibles to mobile devices by introducing transformable physical controls. To switch between these controls quickly, Paddle's transformation model is superior to origami transformations. Paddle therefore allows to switch between completely different controls in a few steps.

(2) *Physical controls with clear affordances.* Bending and folding interactions supported by earlier prototypes of deformable devices, often lack affordances in that it is unclear how these controls map to actions [15, 19]. In contrast, the special-purpose physical controls supported by Paddle offer clear affordances, leaving no abiguity on how to perform an action.

(3) *Input and output in a single integrated space.* In contrast to traditional tangible user interfaces [9], Paddle makes input indistinguishable from its graphical output, integrating them in a single space. As a result, physical controls supported by Paddle provide *inherent feedback*, where feedback is a natural consequence of an action [4].

(4) *Bridging the gap between differently shaped mobile devices.* As a result of being highly deformable, a single Paddle can become a small phone to hold comfortably in your hand, a tablet for reading and an armband while running.

Paddle is also subject to two limitations. (1) The transformation model supported by Paddle might be unknown to the user, making it challenging to switch between form factors. Furthermore, users can always perform transformations that are not supported in a given context. These problems can be alleviated by providing visual help cues [2, 32] to show transformation possibilities. Although our scenario (Figure 2-a,e,g) demonstrates this idea, more generic visualizations are needed in the future. (2) Transforming a device can be time consuming, especially when interactions with a single form factor last for only a few seconds. In these situations, traditional touch interaction on one of the flat shapes supported by Paddle can be used at the expense of the benefits that the custom shape would provide. Alternatively, future Paddle interfaces can support the training of users' muscle memory to switch between shapes in less than a second after some practice. We also see potential in integrating actuators, such as shape memory alloys [25, 10] in our design to ease or even automate transformations.

RELATED WORK

This paper is motivated by work on tangible user interfaces and paper-like interfaces.

Tangible User Interfaces

Researchers have proposed symbolic [5] as well as specialized physical controls [13] in order to encourage eyes-free use and bimanual interaction [5], reduce error [9] and enable physical affordances [13]. On the other hand, researchers noticed that the coupling of physical controls to digital content often reduces the feeling of engagement with digital content, which is more prominent when using direct touch [9].

One interesting approach to take advantage of touch interaction as well as our dexterity with handling physical controls in the real world, is to emulate the physical world on a touch screen. However, we seem to use multiple fingers [31] and hands [30] totally different on interactive screens. This suggests that simulating affordances and physics in a user interface may not be sufficient for encouraging interactions similar to those used for manipulating real world objects [30].

Paddle, however, takes the opposite approach and strengthens the coupling between physical form and digital content by integrating them in a single space. Similar approaches have been explored by other researchers for different purposes [12]. Examples include malleable surfaces for terrain modeling [24], shape displays for physical affordances [6] and tiltable displays to increase realism [1]. These approaches bridge the gap between the physical and digital world, but are often not suitable for general purpose mobile devices. Rudeck et al. [26], on the other hand, present a malleable touch pad to enable differently shaped touch controls on mobile devices. Paddle is different in that the dominant form of interaction is through real world controls instead of touch.

Paper-Like Interfaces

Our prototype can be transformed using folding interactions. Paddle therefore relates to research efforts to incorporate affordances of paper documents in the design of systems used in workplace environments [11] and mobile settings [28]. These flexible paper displays have been used to dynamically adjust screen size [16], navigate through documents by bending [33, 34] and to enable advanced interaction techniques with volumetric images, videos and virtual characters [29]. Lahey et al. [19] and Lee et al. [21] show how bending, folding and more free-form deformations with flexible displays can be used as physical controls in various applications, such as a music player and e-reader. In contrast to the physical controls supported by Paddle, these bend and fold interactions often lack affordances, making it difficult for users to map these interactions consistently to actions [19]. Similar to our research, Foldme [15] demonstrates various folding interactions using a double sided display with predefined hinges. Paddle is different in that it is not based on an origami transformation model. This makes it possible to switch between very different shapes in only a few steps.

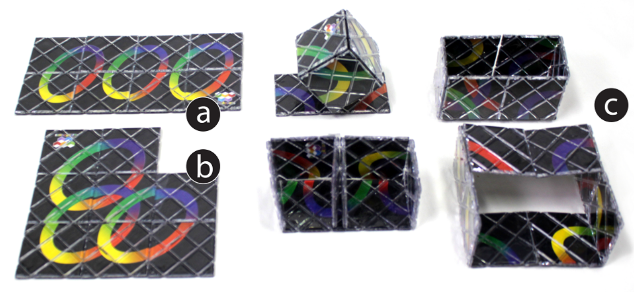

Figure 3. Paddle leverages engineering principles of the Rubik's Magic puzzle: (a) start configuration and (b) end configuration of Rubik's Magic, (c) some of the other supported shapes.

PADDLE PROTOTYPE

Mechanical design

While highly deformable mobile devices do not exist yet, we aim at prototyping devices that provide similar interaction styles. Our prototype, Paddle, is based on engineering principles used in creating 3D puzzles. 3D puzzles have already existed for centuries[1], thus capturing a vast amount of design knowledge in constructing compact mechanisms to enable complex transformations.

Our prototype leverages engineering principles of the Rubik's Magic design (Figure 3), a folding plate puzzle. The original goal of the puzzle is to transform the tiles until the pictures on the different tiles all line up and form an interconnection of rings (Figure 3-a,b).

The design of the puzzle consists of a loop of square sized tiles held together by wires. A special wiring technique, where every wire runs diagonally across the tiles, ensures that all tiles can hinge along two adjacent sides. The location of these hinges is different when a tile is on top or underneath another tile. This technique is an extension of the Jacobs Ladder folk toy principle. Although the puzzle can only be transformed piece-wise, the special engineering principles used in the hinges make it possible to transform the puzzle to various shapes (Figure 3). Figure 4 shows how the wires flip between the tiles to move a hinge from one side of a tile to another adjacent side, when going from a flat form factor (Figure 5-g) to a ring (Figure 5-a).

System Implementation

Paddle uses an eight-camera OptiTrack system to track the topology of Paddle and a projector to provide visual output.

[1] Scientific American, Volume 16 Nr. 15, 1889, page 227

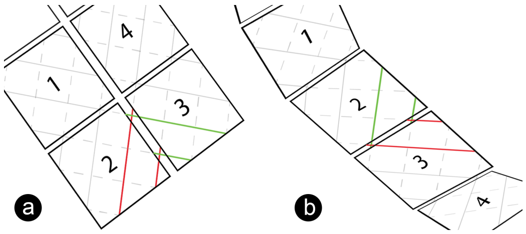

Figure 4. The wiring pattern used for the hinges in Paddle: (a) flat form factor, (b) ring form factor.

This makes our current prototype entirely passive. By attaching five tiny infrared reflective markers on both sides of every tile, we can track the position and rotation of every tile and distort every region of the projected user interface precisely. The Rubik's magic puzzle is painted white to make the projection clearly visible.

To enable touch interactions, markers are attached to the users' fingers. We calibrate every finger to get a precise estimate of the location of the markers on the fingers. When a finger touches our device, TUIO events are generated and translated into touch events using Multi-Touch Vista [2]. Our entire system is implemented in C#/WPF, making it possible to use the Microsoft Surface SDK[3] to have the same look-and-feel as traditional touch screens.

In the future, however, we envision devices similar to Paddle that are entirely self-contained, using electronic connectors to track the topology of the device [8] and tiny integrated displays [1, 22] for output. The wires necessary for interconnecting these displays and sensors can replace the wires used in the hinges to not interfere with transformation possibilities.

INTERACTIONS

Highly deformable mobile devices, such as Paddle, provide many new opportunities for interaction design. We explore this interaction space.

Paddle Transformations

The wide variety of transformations supported by Paddle (Figure 5) can be used for different purposes. Overall, we see three main purposes, which are also highlighted in the scenario (Figure 2):

1. *Shape fits digital content:* Similar to earlier prototypes of deformable devices [15, 16], Paddle can be enlarged to make additional data or tools available (Figure 6-b). Alternatively, the same content can take up a larger space as a way to zoom-in on data (e.g. text or maps). Oftentimes, it is also desirable to have a semantical zoom, providing a more detailed or concise version of the same content when Paddle changes in size. Finally, the size or shape of digital data can be reflected in the physical form of Paddle [20]. For example, in Figure 5 the tiles of configuration (a) can be used to display different elements of a list, (c) has the size of a traditional phone, (e) can fit a portable game console (Figure 6-a) and (g) matches the size of a paper sheet.

[2]http://multitouchvista.codeplex.com/

[3]http://msdn.microsoft.com/en-us/library/ff727815.aspx

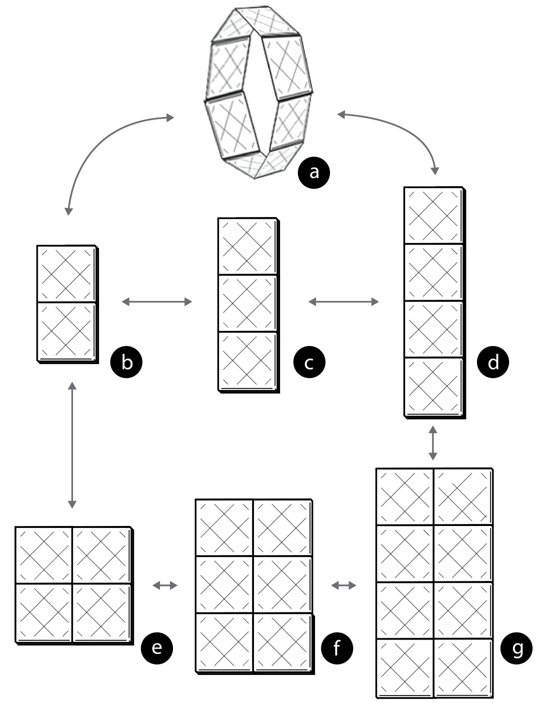

Figure 5. The transformations that are supported by Paddle. This is only a subset of the transformation model of the Rubik's magic puzzle, which is at the basis of our prototype.

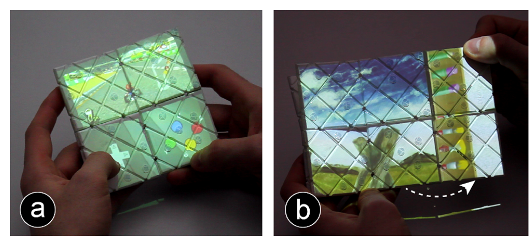

Figure 6. Transformations supported by Paddle can be used for many purposes, for example, (a) a game controller, (b) opening a toolpalet.

2. *Ergonomics:* The shape of Paddle is highly related to the comfort that it provides. For example, it's more comfortable to read a text on a large device (e.g. Figure 5-g), while a device that can be supported entirely by the palm of the hand (e.g. Figure 5-b) provides more comfort (more normal force [3]) during touch interactions. As a result of the hinges used in Paddle, our device can be bended piece-wise to fit more comfortably in the hand or back pocket, to make a larger region accessible for thumb interactions or to position audio sensors closer to the mouth and ear to improve voice and sound quality during calls[4].
3. *Physical controls (i.e. Paddle controls):* Folds [15] and bends [19] have already been used as physical controls in user interfaces. As Paddle supports a lot more transformations, the device can be transformed into various special-purpose controls that provide better physical affordances. We elaborate on these Paddle controls in the next section.

[4]http://www.lgnewsroom.com/newsroom/contents/63988

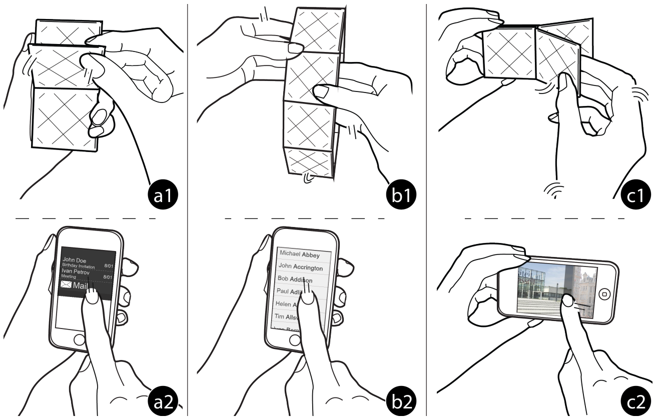

Figure 7. Paddle shows how physical controls (i.e. Paddle controls) for (a1) peeking, (b1) scrolling and (c1) leafing can be brought to mobile devices as alternatives for traditional touch interactions (a2,b2,c2).

In many situations, these purposes are not mutually exclusive. For example, the large flat shape shown in Figure 5-g can be a suitable shape to display a full page of text at once, but doing so also provides great comfort for reading [14].

To communicate the transformation possibilities at any moment, Paddle provides visual help cues to guide the user, as shown in our scenario (Figure 2-a,e,g). These cues are only displayed when the user places his fingers at predefined spots, visualized by virtual fingers (Figure 2-b,d). This approach (inspired by TouchGhosts [32]) reduces visual clutter and shows how to hold Paddle to perform different transformations. On the other hand, users can always choose to perform transformations that are not supported by the current form factor (Figure 5). In these situations, help cues are provided to backtrack to a supported configuration.

Paddle Controls

Deformable devices can be transformed for different purposes, as discussed in the previous section and demonstrated by earlier prototypes [15, 16, 19]. The potential of highly deformable devices to transform to various physical controls has to our knowledge not been investigated before. Although, FoldMe [15] and PaperPhone [19] show how bends and folds can be used as physical controls, they lack affordances compared to traditional tangibles [13] and touch screens, as it is often unclear how folds and bends map to actions [19]. In contrast, Paddle can be transformed to various physical controls (Figure 7), each providing customized physical affordances for the task at hand. Figure 5 shows how to switch between the physical controls supported by Paddle: configurations (b) and (e) support peeking (Figure 7-a), configuration (a) supports scrolling (Figure 7-b) and configuration (b) also supports leafing (Figure 7-c). In this last configuration, pages continuously flip from one side to the other to simulate an unlimited number of pages.

Paddle controls are different from traditional tangibles in that, similar to direct touch, Paddle combines input and output in a single space, making input indistinguishable from its graphical output [9]. Although direct touch and Paddle controls both offer clear affordances, the interaction styles they adopt are very different: direct touch relies on pointing as sole interaction technique whereas various grasps are used to interact with Paddle controls.

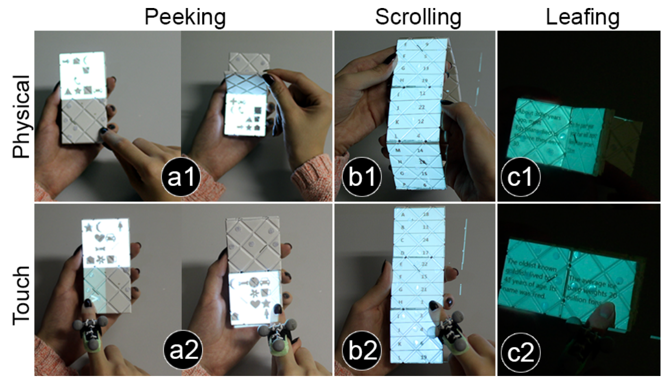

Figure 8. Our first study compares (1) physical to (2) touch interactions for (a) peeking, (b) scrolling and (c) leafing tasks.

Below, we conduct an in-depth study to investigate the benefits one gets from the physicality of Paddle controls compared to traditional direct touch interactions on mobile devices.

STUDY 1: THE BENEFITS OF PADDLE CONTROLS

In a first experiment, we investigate the potential benefits of Paddle controls compared to traditional direct touch input typically used on mobile devices. We picked *peeking*, *scrolling* and *leafing*, as they are good representatives of Paddle controls and equivalent interactions are supported on many touch screens (Figure 7).

Tasks

Since we are interested in measuring differences in skills and the resulting cognitive effects when using Paddle controls, our tasks are based on best practices for measuring skill and motor behavior [27]. Various pilot studies were conducted to calibrate the difficulty of the task sets.

Peeking

For this task, 9 different symbols (out of a set of 17 different symbols e.g. a circle, triangle, star) are displayed at random positions in a grid (Figure 8-a). When performing a peeking interaction, all 9 symbols plus an additional symbol become visible at random locations on the window that is revealed (Figure 8-a). The original window then becomes invisible to encourage more peeking interactions. The task is completed when the user identifies the additional symbol. In the physical condition, the peeking window is located on the upper side of the device, while in the touch condition, the peeking window can be opened by dragging the window from left to right which reduces the effect of occlusions caused by the hand.

Scrolling

The main goal of the scrolling task is to encode a given word into a series of digits, as fast as possible, using the encoding list displayed on the device (Figure 8-b). The user can scroll through a look-up table that has 26 entries, one for every letter in the alphabet, using Paddle. Four entries of the encoding table are displayed on every tile of Paddle, leaving 1.5

tiles empty between the end and the starting point of the loop (Figure 8-b1). In the touch condition (Figure 8-b2), the loop is simulated, making it possible to scroll infinitely, similar to the physical condition. Different encoding tables are used for every word. Although words with the same length are used, different letter combinations require different amounts of scrolling. We compensate for this by generating encoding tables that requires the same amount of scrolling for every condition.

Leafing
For the leafing interaction, participants leaf through a book of 10 pages in which facts about various topics are shown on every page (Figure 8-c). Participants can leaf through the book and read the facts for 70 seconds. Afterwards, 4 facts are presented, but some of the facts have their details changed. Participant are asked if the fact is correct (distractor task) and have to estimate the page number of the fact in the book (main task).

Variables
For the peeking and scrolling task, we measure *task completion time* as the main measure of performance. For the peeking tasks we also measure the *number of peeks*. Since both tasks are feasible with a very low error rate (confirmed by the pilot studies) under all conditions, a new task was given in the rare occasions when participants failed to give the right answer. For the leafing task, the *error rate* for estimating page numbers and the *grade* (percentage) for detecting correct facts was measured.

Procedure
We recruited 16 participants (2 female, mean age 25) from our university campus. All were right-handed. The study used a within subjects design. For each of the three tasks, the physical and touch condition, were presented in a counterbalanced order. Additionally, the task sets were switched over the conditions to balance potential differences in task difficulty.

For every condition (physical, touch), the participant received instructions about how to perform the task. For the peeking and scrolling task, participants were instructed to complete the task as fast as possible. For the leafing task, we instructed participants to focus on the distractor task (correctly identifying wrong facts). Participants controlled a footswitch to start and end every task. Every condition started with a series of practice trials until the participant understood the interaction style and felt comfortable with the system. For the touch conditions, the participant's pointing finger was instrumented with markers to enable touch interaction on Paddle.

After every condition, a modified version of the ISO 9241-9 questionnaire with dependent rating scale for testing input devices was filled in, with only a single fatigue category and an additional "intuitiveness" category. All interactions were recorded on video. The average experiment completion time was approximately one hour. After a participant completed the experiment, there was an informal discussion during which the participant was asked to explain his interaction preferences.

Hypotheses
We expect that peeking using touch requires participants to focus on both the content in the peeking window and how the entire peeking window is moving when it is opened or closed. When using physical peeking, on the other hand, participants rely on tactile sensory feedback to interact with the peeking window and can thus better focus on the visual information that is presented (i.e. our symbol comparison task). We therefore hypothesize that:

H1: Physical peeking is faster than peeking using touch.

We expect that physical scrolling helps users to build up spatial memory and better uses sensory motor skills compared to touch. We therefore think that with physical scrolling, participants will immediately grasp at elements along the ring instead of scrolling through all elements, as is necessary with touch. We therefore hypothesize that:

H2: Physical scrolling is faster than scrolling using touch.

Physical leafing with Paddle is a more expressive way to navigate through a book compared to swipes using touch. We therefore expect that with physical leafing, participants are more aware of the position of the current page in the book at any time and are thus better at recalling the structure of this book. We therefore hypothesize that:

H3: Physical leafing results in more accurate estimates of page numbers.

Results
We collected 384 data points for the peeking tasks, 384 data points for the scrolling tasks and 512 data points for the leafing tasks. After removing error trials (respectively 3.1%, 2.1% and 0.2%) and outlier response times for the peeking and scrolling task (respectively 1.6% and 1.6%), we were left with respectively 366, 370 and 511 trials in this analysis. Trials were labeled as outliers for each condition when exceeding the mean by three standard deviations.

For every task, we aggregated the trials of every participant, and ran a repeated-measure ANOVA. For the peeking task, we found a significant difference between physical and touch (13.9s vs. 16.5s, $F_{1,15} = 5.75$, $p=0.03$), as shown in Figure 9-a. This confirms H1. Contrary to *H2*, we did not find a significant difference between physical scrolling and scrolling using touch ($p=0.93$) (Figure 9-b). As shown in Figure 9-c, we found a significant difference between physical leafing and leafing using touch, with the physical condition resulting in 46% more accurate page estimates ($F_{1,15} = 62.97$, $p<0.001$). This confirms H3. Although not included in our hypothesis, when physically leafing through pages, there are significantly fewer errors when participants were asked if the presented fact was correct (73.3% vs. 57.4%, $F_{1,15} = 25.79$, $p<0.001$). Additionally, participants leafed significantly more in the physical condition (15.2 vs. 12.8 leafs, $F_{1,15} = 7.26$, $p=0.02$).

Subjective User Feedback
The comparative ISO 9241-9 questionnaire confirmed our quantitative results for the peeking interaction (H1). Participants reported that they found physical peeking significantly

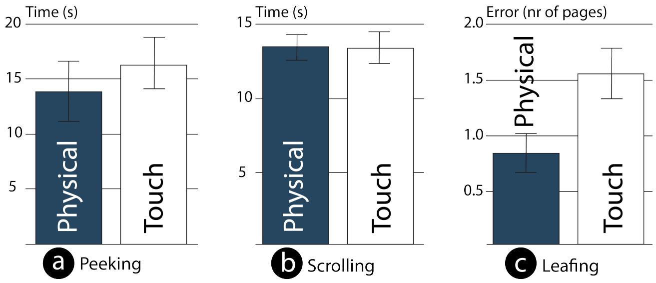

Figure 9. The results of study 1 comparing physical and touch for (a) peeking, (b) scrolling, (c) leafing.

better on the scale of force, intuitiveness, accuracy, speed, comfort, smoothness and overall operation. Physical peeking performed equally well as peeking using touch on the scales of effort and fatigue. Some noticeable comments during the interview also help to further explain our quantitative results: "When using touch, I have the feeling that my eyes are following my finger unconsciously.", "In the physical condition, you intuitively know how far to open the peeking window to reveal all content. In the touch condition, the peeking window can have any size.", "In the physical condition, the content does not move.", "Touch requires better targeting as one needs to stop at the border of the device to prevent losing track of the touch point."

Similar to the quantitative data, there was no clear preference in interaction style for scrolling (H2). However, participants agreed that physical scrolling requires significantly more effort than scrolling using touch. Contrary to H2, five participants mentioned during the interview that they did not know how many tiles to scroll with the physical ring to go to a specific letter. Two of these participants commented that they were confused because multiple items were displayed on a single tile. Four other participants mentioned that their performance in the physical condition could have been influenced by the latency of our system. This latency was much more noticeable when physically scrolling through the list, because the device moved a lot more.

Contrary to the quantitative results for the leafing task (H3), participants rated leafing using touch significantly better on the scales of force, effort, speed, comfort and smoothness. Physical leafing performed equally well as leafing using touch on the scales of intuitiveness, accuracy, overall operation and fatigue. When participants were asked during the interview which interaction style they preferred overall for the leafing task, the ratings of the questionnaires were confirmed, with 11 participants preferring touch, 3 preferring physical and 2 undecided. However, six of the participants who preferred touch, mentioned that they would prefer physical leafing if the leafing mechanism was more comfortable. Many of these participants commented that when leafing physically, the device was less comfortable to hold as pages have to flip back from behind in order to have a book with an unlimited number of pages. One participant mentioned that he felt more confident about the page numbers he gave when physically leafing through the book.

Discussion

Overall, hypotheses H1 and H3 were confirmed. Our study clearly shows that physicality provides benefits for leafing interactions. Participants could better recall the structure and content when physically leafing through the book.

Although we also measured a significant benefit for physical peeking compared to touch, it remains unclear if the direction for opening the peeking window in the touch condition played a significant role in the effect that we measured. As one participant correctly noticed, the direction in which the peeking window had to be pulled out in the touch condition might have slowed him down, because the end point of the dragging movement was near the border of the device, which introduces a speed-accuracy trade-off, known as Fitts' law. Additionally, our experiment did not confirm our second hypothesis, in that we did not measure a difference between physical scrolling and scrolling using touch.

We identified four factors that require further investigation in a second experiment, in order get a deeper understanding of the benefits of Paddle controls. Three factors focus on scrolling, for which we could not yet find any significant difference. The last factor focuses on peeking, for which we already found significant differences.

1. *Does the mapping of digital items to physical elements contribute to the efficiency of physical scrolling?* We observed that displaying multiple digital items (in our case 4 letters of the alphabet) on a single physical element (in our case a single tile of the physical ring) introduces a mismatch between tactile and visual information and confused participants, as they were not used to think in terms of groups of 4 items. To investigate this, we will compare physical scrolling to scrolling using touch with a list of 8 elements, one for every tile in the physical ring (Figure 10-b1,b2).
2. *Does visual realism contribute to the efficiency of physical scrolling?* A lack of visual realism in the physical scrolling condition, due to the latency of our prototype, might have influenced the performance of the physical scrolling condition more than the touch condition, as physical scrolling requires more and faster movements of the device. To measure this effect, we will compare a physical ring with 8 elements printed on it (Figure 10-b3) to the condition where 8 elements are projected on the ring (Figure 10-b2).
3. *Does the quality of scroll inertia contribute to the efficiency of scrolling using touch?* Although inertia was enabled on the scroll list in the touch condition, our prototype implementation could have influenced the performance of scroll inertia, as we tracked the position of the fingertip to the surface of our device, which can slightly vary over different hand/finger postures. To measure this effect, we will compare scrolling using touch on Paddle (Figure 10-b2) to scrolling using touch on a tablet on which exactly the same list is displayed (Figure 10-b4).
4. *Does homing towards a target near the border of a device when opening a peeking window, contribute to the efficiency of peeking using touch?* For this, we will evaluate touch and physical peeking in another direction, which eliminates precise targeting and similar to the previous ex-

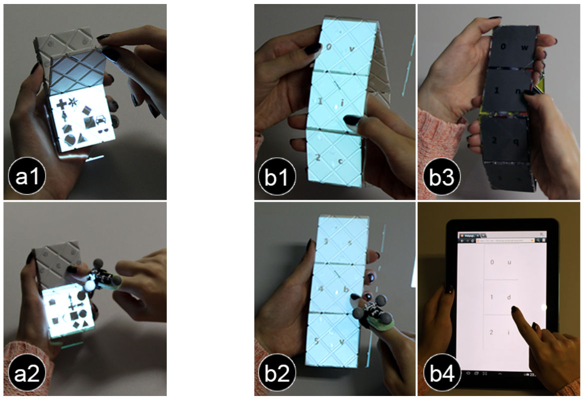

Figure 10. Our second study further investigates the factors contributing to the efficiency of Paddle controls and touch interaction for peeking and scrolling.

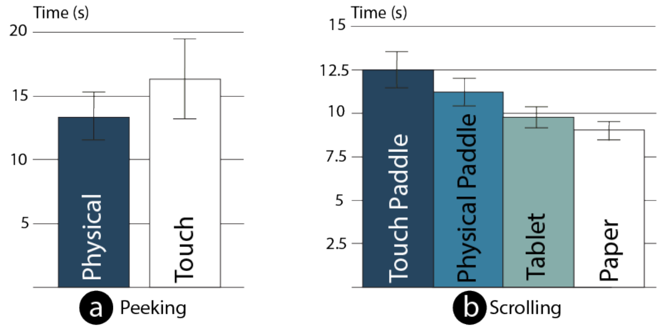

Figure 11. The results of study 2, investigating the factors contributing to the differences between physical and touch for (a) peeking and (b) scrolling.

periment, reduces the effects of occlusion by the hand to a minimum (Figure 10-a).

STUDY 2: CONTRIBUTING FACTORS

To understand the factors contributing to the differences between physical and touch for both our peeking and scrolling interaction, we conducted a second study. We evaluate the relative effect of the location of the target position when opening a peeking window using touch by evaluating peeking in another direction (Figure 10-a). For the scrolling task, we investigate the importance of mapping digital to physical items (Figure 10-a-b), the potential effects of visual realism for the physical condition (Figure 10-d) and scroll inertia for the touch condition (Figure 10-c).

Modifications to the tasks

For the peeking conditions, we used task sets similar to the ones used in our first experiment, but we displayed them on different regions of Paddle (Figure 10-a). For the scrolling conditions, the task sets were slightly adapted, as we now have lists consisting of only 8 elements (compared to 26 in the first study). We therefore generated new look-up tables, which translate 8 ordered numbers (0-7) to letters. The resulting word is nonexistent, which prevents participants of giving the answer before looking up all the numbers. Participants were also explicitly instructed to look up the numbers in the order in which they were displayed. We also increased the number of items that participants had to look up, from 4 in the previous study to 5, in order to encourage more scrolling and compensate for the shorter look-up tables.

Procedure

We recruited 16 participants (4 female, mean age 26), 8 of which were randomly chosen from our previous pool. All were right-handed. The study used a within subjects design. For the peeking task, the conditions were fully counterbalanced. The four scrolling conditions were presented in a counterbalanced order using a balanced Latin square. Additionally, the task sets were counterbalanced over the conditions for every task, in order to balance potential differences in task difficulty. The entire experiment lasted one hour on average, after which there was an informal discussion with the participant.

Hypotheses

H4: Physical peeking outperforms peeking using touch, independent of the location of the peeking window.

H5: Physical scrolling outperforms scrolling using touch when displaying exactly one digital element on every tile.

H6: Physical scrolling with the paper prototype outperforms physical scrolling with Paddle using projection.

H7: Scrolling on the tablet outperforms scrolling on Paddle using touch.

H8: Physically scrolling with the paper prototype outperforms scrolling on the tablet.

Results

We collected 384 data points for the peeking task and 768 data points for the scrolling task. After removing error trials (respectively 3.6% and 2.6%) and outliers (respectively 2.1% and 0.7%), we were left with 362 and 742 trials, respectively. We analyzed the results using repeated measures ANOVA. All post hoc comparisons used Bonferroni corrected confidence intervals.

Consistent with the findings of our first study, we found a significant difference between physical peeking and peeking using, touch as shown in Figure 11-a (13.4s vs. 16.4s, $F_{1,15} = 5.45$, p=0.03), confirming H4.

Figure 11-b shows the overall trend of our results for the scrolling tasks. There was a significant main effect ($F_{3,45} = 50.5$, $p<0.001$). Pairwise tests show that participants were significantly faster with physical scrolling than scrolling using touch on Paddle (11% faster, p=0.02). Furthermore, physically scrolling with the paper prototype outperformed physical scrolling with projection (20% faster, $p<0.001$). Scrolling on the tablet was significantly faster than scrolling on Paddle using touch (22% faster, $p<0.001$). Finally, physically scrolling with the paper prototype was significantly faster than scrolling using touch on the tablet (9% faster, p=0.01), confirming H5-H8.

Subjective User Feedback

Although all participants agreed that physical scrolling was more tiring than touch, 11 participants preferred physical scrolling with the paper prototype and only 3 participants preferred the tablet (2 participants were undecided). 13 participants agreed that they could easily remember the position of elements along the physical ring. Five participants even noticed that overshooting targets occurred more often on the tablet than when physically scrolling with the paper prototype.

FINDINGS OF STUDY 1 AND STUDY 2

Our two studies combined show that physical controls supported by Paddle have certain benefits compared to traditional direct touch interaction techniques.

Starting with the peeking interaction technique, our first and second study reveal that physical peeking is significantly faster and subjectively preferred compared to peeking using touch (H1+H4). We therefore conclude that physical peeking outperforms peeking using touch. Our results suggest that peeking using touch requires users to focus on both the content in the peeking window and how the window is moving. When using physical peeking, on the other hand, users rely mostly on tactile feedback to interact with the peeking window and can therefore better focus on the visual information presented in the task at hand.

For the leafing interaction, our first study shows that physical leafing is a slower and more tiring interaction compared to touch, but results in an improved recall of the structure and content of a book (H3). Similar results have been found in studies on paper vs. e-readers [14]. Their results were, however, motivated by the fact that paper books facilitate the process of picturing content on pages, as real books provide implicit cues (e.g. thickness) about where you are in the book. Our finding suggests that the physical leafing interaction itself is a large contributing factor to the benefits one gets from interacting with real books. So in addition to all efforts of making e-readers look and feel like real paper [33, 34], Paddle shows how certain benefits one experiences with real books can be brought to devices using physical controls.

For the scrolling interactions, our first study indicates that physical scrolling is more tiring than scrolling using touch. No other significant differences between these input modalities were found (H2). Our second study, however, shows that when displaying exactly one item of a list on every tile of the physical ring, participants were significantly faster with physical scrolling than scrolling using touch (H5). In the physical scrolling condition, users can locate elements very precisely and are thus able to directly grasp at elements further in the ring compared to the touch condition, in which scrolling through all elements is necessary. This suggests that users are better able to use their sensory motor skills and build up spatial memory when scrolling physically.

Our second study also shows that visual realism plays an important role when physically scrolling through lists. Physical scrolling with the paper prototype turns out to be significantly faster than both physical scrolling with Paddle with projection (H6) and a traditional tablet with scroll inertia enabled (H8). The latter result suggests that scrolling with future Paddle devices with perfect visual fidelity (i.e. with real displays) will result in faster acquisition of elements compared to traditional lists on touch screens with scroll inertia.

Physical scrolling through longer lists

Our first and second study only show significant benefits for physical scrolling when mapping every item of a list to a single physical element of our ring (i.e. same number of digital and physical items). It remains unclear how to efficiently support longer scrolling lists with Paddle. We therefore conduct a smaller final study in which we compare physical scrolling through longer lists using Paddle to scrolling through the same list on the tablet. The same tasks are used as in the second study, but now the look-up tables are twice as long. Instead of displaying multiple items of the scrolling list on a single physical element at the same time, as we did in the first study, we now wrap the scrolling list multiple times around the physical ring. We asked 8 participants to perform both conditions in a counterbalanced order. Our analysis is based on 185 valid trials.

Although our second study shows that scrolling using touch on the tablet was significantly faster than physically scrolling with projection, we did not find a significant difference between these two conditions when the list is twice as long (p=0.79). These results suggest that participants gained more benefits from physicality when the lists become longer. While users commented that physical scrolling is more tiring with longer lists, analyzing our video recordings clearly shows the dexterity that participants have when scrolling physically through the long lists. Even though participants noticed the latency of our system when physically scrolling using Paddle as in study 1 and 2, participants knew almost exactly how many times to turn the ring to get to a specific item. Our second study shows that visual realism is an important contributing factor for the efficiency of physical scrolling with Paddle. We therefore expect that for longer scrolling lists, future Paddle devices with perfect visual fidelity (i.e. with real displays), will also outperform direct touch.

CONCLUSION & FUTURE WORK

In this paper, we presented the concept of highly deformable devices that can be transformed into various special-purpose controls in order to bring physical controls to mobile devices. We demonstrated this concept by showing one possible implementation, called Paddle. This prototype was based on the design of the Rubik's magic puzzle. An in-depth study revealed that the physical controls supported by our prototype provide several benefits compared to touch supported by traditional mobile devices, such as being able to better utilize sensory motor skills, improved abilities to build up spatial memory and improved comprehension of content. Although Paddle is still a prototype, we believe that our findings can inform and encourage the design of future highly deformable devices and their abilities to bring physical controls to mobile devices. As future work, we plan to investigate how Paddle interfaces can be designed to help train users' muscle memory over time in order to switch between shapes more quickly.

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