Paperbox – A toolkit for exploring tangible interaction on interactive surfaces

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ABSTRACT

There is a well-established culture of early prototyping when designing digital interactive systems, such as paper prototyping and wireframe methods. The culture of designing physical objects is somewhat different: early explorations of form is still prototyped via 2D sketches or renderings, but - mostly because of the construction effort involved - prototyping of actual physical objects is deferred to later stages. A problem occurs when designing mixed physical-digital systems, such as tangible user interfaces (TUIs) on interactive surfaces: the high degree of interactivity means that early prototyping is vital, yet there is no viable process for prototyping both the physical and digital aspects simultaneously on a low-fidelity (low-fi) level. Our solution is *Paperbox*, a toolkit for exploring design ideas for tangible interaction on interactive surfaces. It supports the early exploration of different form factors and immediately provides digital interactivity for the low-fidelity TUI prototypes built with it. We observed our toolkit in use in various settings: as a brainstorming tool by junior designers; in the development of a consumer electronics product in a large industrial company by senior designers; and in a usability study comparing the effect of different levels of fidelity on the outcome. The lessons learnt will enable others to replicate and extend our approach.

Author Keywords

Tangible User Interface, Design Process, Prototyping.

ACM Classification Keywords

H 5.2. Information interfaces and presentation.

General Terms

Design.

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INTRODUCTION

Tangible interaction has established its place within the HCI community over the last two decades [16]. Researchers typically contribute eloquent and novel TUI designs, studies of TUIs in use, or technologies for building TUIs. Yet unlike traditional HCI, there has been relatively scant effort in considering how TUIs can be designed from scratch. That is, there is little guidance to formal design process nuances, or specific guidelines that designers and engineers can follow when facing the task of creating a new tangible user interface. This is especially problematic as the design of tangible user interfaces is particularly challenging in that it demands consideration of *both* the form factor and the interconnected interactive behavior.

Our focus in this paper is on the role of low-fidelity prototypes within a TUI design process. As with all design, early prototyping is critical for getting the design *right* [3]. Without early prototyping, it is far too easy to produce poor designs. Low-fidelity prototyping in other contexts, such as graphical user interface (GUI) prototyping, is well known to be important for quickly evaluating a large variety of design alternatives and choosing what appears to be the *most promising* one for further development. Unfortunately, such a systematic design practice has not yet been elaborated or described in the realm of TUI design. Given this situation, our goal was to explore the role of low-fidelity prototyping within TUI design on interactive digital surfaces.

To achieve this goal, we built and evaluated a relatively simple and very low-cost, low-fidelity (low-fi) TUI toolkit called *Paperbox*. It provides templates that designers can use to rapidly create a variety of basic objects, which are combinable to create compound objects. *Paperbox* objects can also interact with digital surfaces when annotated with conductive ink. The ink forms unique patterns that are recognized by the surface, and can be used interactively to drive software. *Paperbox* will be explained in greater detail later in this paper.

We conducted three studies to evaluate the effectiveness of *Paperbox* within the TUI design process. Our first lab study involved students of various disciplines, who were asked to

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develop a TUI application using either *Paperbox* or Post-it® notes. Our second industrial case study involved senior level industrial designers who incorporated *Paperbox* into their own design processes for developing a next-generation consumer electronic product. Our final lab study examined how TUI prototypes – ranging from low to high fidelity – affected the result of a usability study. Overall, our work contributes a first-generation toolkit for creating low-fi TUI objects and an initial evaluation of the role of low-fidelity physical objects in the TUI design process.

RELATED WORK

Our work compares to and builds on results and techniques from the fields of *graspable* interaction and prototyping UIs, and it also uses the notion of basic shapes and form factors as used in psychology and related fields of design.

Graspable Interaction

Graspable interaction was popularized by Ishii et al. [10, 11] as an essential aspect of tangible user interfaces, with many TUI designs introduced over the years. For example, Ullmer et al.'s *Metadesk* investigated the practical use of graspable interactions on interactive surfaces [18]. The authors mapped 2D GUI interface icons to 3D equivalents called *phicons* (physical icons) suitable for graspable interaction, which when grasped affected what appeared on the surface. Rekimoto, Ullmer and Oba created *Datatiles* [14] that directly connected a *phicon* with its digital manifestation. More specifically, a *Datatile* was a tangible see-through graspable tile. When placed on an interactive surface, it would reveal interactive graphics immediately underneath it, the content of which was mapped to the tile's meaning. Our work extends these concepts, and we provide ways for developers to easily explore and consider various physical forms (phicons) and their *mapping* to digital content in the early stages of the design process.

Prototyping and its Bottlenecks

Hornecker [9] highlights the need for rapidly prototyping graspables. She argues that the users can, even if they have correctly understood, wrongly apply the *mapping* between the physical artifact and the respective digital behavior. In particular, she states that iterative prototyping and early pre-testing in coordination with users is the only opportunity to get the design *right* and produce an enjoyable and usable outcome [3]. This issue likely arises because the affordances of such hybrid interactions are critical, perhaps even more so than in standard GUI design [13]. Yet there is still no formal design process that lets creative designers explore such affordances.

While prototyping tools are readily available for GUIs, they are rare in tangible interaction. Many GUI prototyping tools let developers explore designs (including interactive behaviors) at different fidelity levels. In contrast, only few tools are available for an equally detailed investigation of form factors. For example, Sanders et al. [15] proposed a variety of physical toolkits and methods to support creative thinking while designing products. However, these methods all focus on non-digital explorations, which are quite different from the hybrid systems that we are concerned with. As Avrahmi et al. [1] argues,

> "the design of physical interactive products (such as handheld devices), often suffers from a divide between exploration of form and exploration of interactivity. This can be attributed, in part, to the fact that working prototypes are typically expensive, take a long time to manufacture, and require specialized skills and tools not commonly available in design studios."

Our work specifically addresses this divide. *Paperbox* directly targets graspable interactions on interactive surfaces, and lets designers simultaneously explore interactivity and form factors.

A number of researchers suggested that a major bottleneck in developing hybrid interactions lies in the difficulty of linking the phicon to its digital counterpart. A current approach is to make easy-to-program hardware available to designers (switches, actuators, sensors, etc.), which can be embedded into physical objects and then linked to a controlling program [1, 7]. Our work differs in that it considers the difficulty of exploring alternate form factors as yet another bottleneck in the design process that needs to be addressed.

Basic Shapes and Form Factors

Biederman provides a catalogue of basic objects that he referred to as geometrical icons (geons) [2]. His theory of object recognition states that humans recognize different objects by deconstructing them into geons (shown in Figure 1).

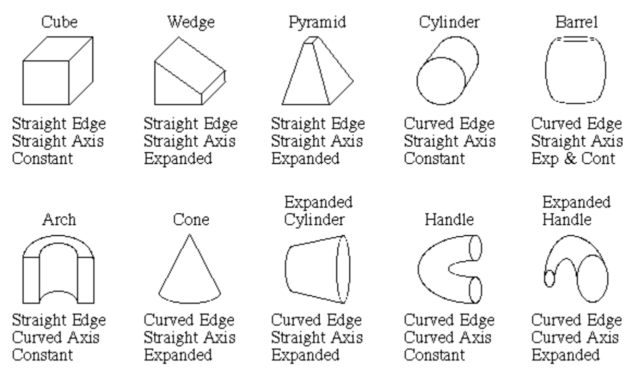

Fig. 1. Simple geometrical forms as described in Biedermans' theory on object recognition [2].

Rapid prototyping of alternative form factors is equivalent to creating a physical sketch. Buxton argues that sketches supporting user experience design need to be disposable, plentiful, quick to make and ambiguous (i.e., they can be openly interpreted) [3]. A related notion is that sketches need to be rapidly constructed by composing basic sketch elements together, such as the lines, circles, simple objects and shapes [6].

Given the above, we believe that a prototyping toolkit should be based on a collection of low-fi simple physical objects that can be used as they are or combined together to compose more complex objects. We were inspired not only by Biederman's basic objects, but by various systems that let people compose paper-based 3D objects (albeit not for interaction). For example, Eisenberg et al.'s *Hypergami* toolkit supports the mathematical craft of creating a variety of simple geometric objects via an online platform [4, 5]. *Pepakura*[1] is somewhat similar but also promotes online sharing and replication of paper objects.

Our second goal was to develop a low-fidelity prototyping technique for TUIs that works with interactive surfaces. Physical objects would be the input device, while the surface would be the graphical and auditory output device.

PAPERBOX

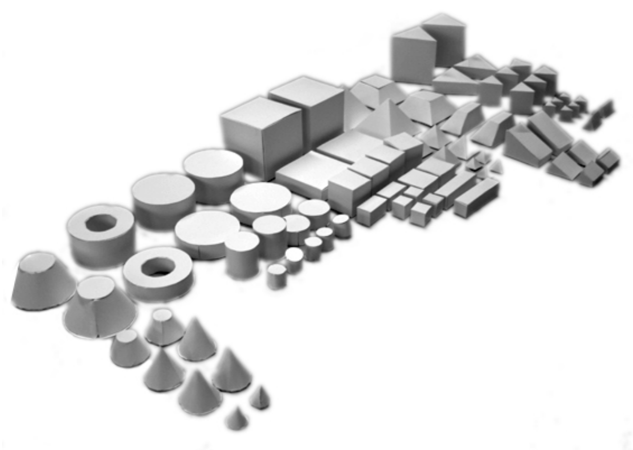

Fig. 2 An initial version of *Paperbox,* a toolkit for the rapid exploration of form factors considering graspable interaction concepts in early process stages.

Paperbox is intended to help developers of TUIs envision interaction design concepts and to ease communication with potential users during the early phases of the design process (see Figure 3). Yet as discussed, one bottleneck in prototyping TUIs is the actual construction of the 3D objects. To mitigate this difficulty, we created the *Paperbox* toolkit.

Paperbox provides designers with a variety of templates that, when cut out and assembled, define TUI primitives. Using these templates, the designer can quickly create various reasonably robust 3D shapes out of thin cardboard and glue (e.g., cubes, pyramids, cylinders). Figure 2 illustrates some of the basic building blocks available in *Paperbox*. While these objects can be used as they are to create graspable interfaces, the designer can easily combine them using magnetic tape to form more complex TUI objects, such as those in Figure 5. Our TUI primitives can thus be understood as the terminal symbols of a TUI language.

[1] http://www.tamasoft.co.jp/pepakura-en/

Paperbox currently supplies these building blocks in various sizes, where their shapes are based on the previously mentioned theory of *geons* [2]. This suffices to provide enough combinable basic shapes for exploring a wide range of more complex form factors. These form factors are, in the case of TUIs, strongly interconnected to the concept of object *affordances,* as discussed by Norman [13].

Paperbox Components

Our first version of *Paperbox* contains 90 different low-fidelity elements, made of 1.5 mm thick white cardboard (see Figure 2). It comprises 30 individual object shapes in three sizes each to provide different volumes: small (1.5 cm diameter), medium (3 cm) and large (6 cm). These elements can easily be attached to each other using magnetic tape for creating more complex and abstract forms of early TUI representations (see Figure 5).

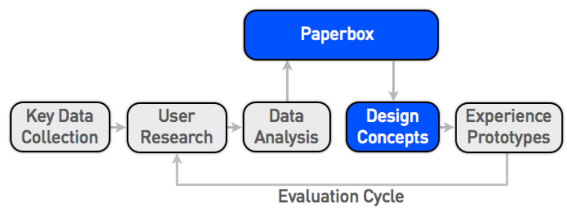

Fig. 3 *Paperbox* helps designers explore form factors of TUIs in those process stages in which they consider alternative design concepts.

Linking objects to digital interaction

Paperbox also enables the rapid creation of tangibles that can work immediately on interactive surfaces. To link them to the respective software, designers draw distinctive lines on each object using a conductive ink pen. This makes the objects recognizable by any capacitive touch screen (see Fig. 4).

Through standard programming, these tangibles can then be linked to particular digital interactions. We first introduced this method of linking in [19]; *Paperbox* is a next generation iteration of that work as it applies the linking concept to a broad variety of forms.

Initial Evaluation

While simple in concept, we believe that *Paperbox* objects can have a strong role in early formal and informal participatory design sessions. In particular, we hypothesize that *Paperbox* objects can:

Fig. 4 Sketching conductive ink on a *Paperbox* object (left), and then using it to interact with a tablet (right) [19].

- stimulate the *flow* of communication, and
- provide insights into which physical appearance is the most appropriate representation – in terms of metaphor, aesthetics, or ergonomic qualities – for the attached digital behavior.

In order to further substantiate our initial assumptions, we conducted two exploratory studies *of Paperbox,* one involving junior designers in a lab setting, the other involving senior designs in an industrial setting.

LAB STUDY

In the first exploratory study, we observed interdisciplinary design teams who used *Paperbox* vs. Post-it® Notes for a brainstorming task: to envision interaction concepts for TUIs on interactive surfaces (see Figures 5 & 6).

Participants and Setup

We recruited twelve participants, (seven female, average age 25 years). Six were students of media informatics, one was a student of the arts and multimedia, two were students of pedagogics, one was a student of computer science, one was a research assistant and one was obtaining a Ph.D. in social psychology. They were divided into groups of three and asked to envision and discuss the physical properties and interaction behavior of a TUI in two applications, one for browsing photos and one for editing images. Both applications were targeted for the Microsoft *Surface*. In one session, the participants used *Paperbox* to express their ideas and visions, while in the other they used Post-it® Notes. The study had a within-subjects design with factors *application* (photo browsing, image editing) and *ideation medium* (Paperbox, Post-it® Notes). Each session lasted 15 minutes.

Data and Analysis

Tasks and methods were assigned to the groups via a 2 x 2 Latin square. After completing all four conditions, the participants were given a questionnaire consisting of five-point Likert scale questions (1 = *strongly disagree* to 5 = *strongly agree*) combined with open questions comparing the perceived communicational aspects of both methods. All sessions were videotaped for analysis, and additional photographs of the setup were taken.

Outcomes

The benefits of the physicality of *Paperbox* objects were immediately apparent when examining the variety of ideas for the given design context. Figure 5 depicts several *Paperbox* interaction concepts produced by the teams. One team, for example, imagined objects that would be stacked atop each other and allow for different photo browsing controls within a time-based interface (see Figure 5, left bottom). By extension, different objects would represent and affect different time units. The larger object, stacked on the bottom of the TUI, would allow the browsing of years, the next object up would affect months, days, and smaller units of time so as to quickly give the user direct access to stored albums and individual images without having to navigate through sub-menus.

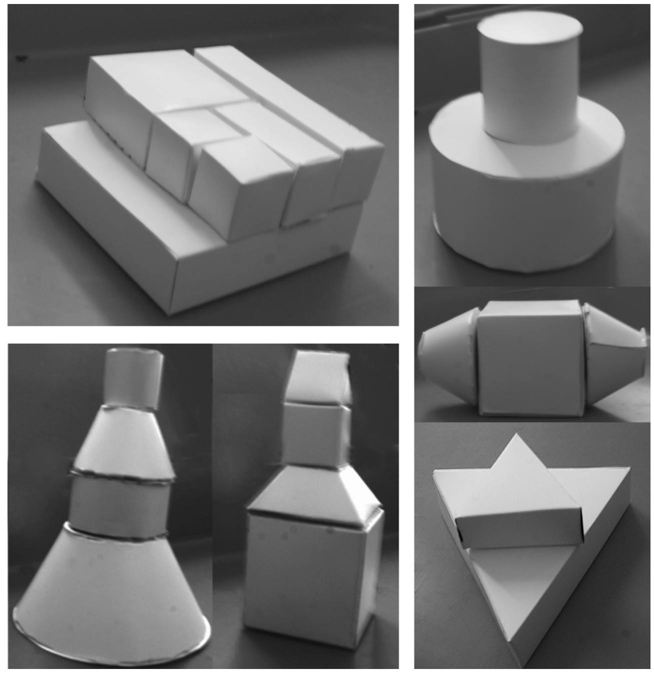

Fig. 5 Early instantiations of TUIs for a photo application expressed through the aid of *Paperbox*.

Two other teams produced an interaction design idea that involved detachable objects, which could individually be used for different purposes (see Figure 5, right top and bottom). They imagined that one object would remain on the interactive surface and the other, smaller, object could be removed and taken with the user, and could then act as *data storage* or a *physical transmitter* of selected images to other devices in other places (e.g., public displays). An additional idea included an object that would act as a *playhead* on a digital time line (see Figure 5, right middle). Small objects would be detachable and serve as *constraints* for an envisioned *digital timeline,* while the bigger object would navigate through different time periods by being moved along the *time-line* like a big slider. Some of these ideas were subsequently implemented on an interactive tabletop computer (see Figure 6) and served as a contextual framework for a later follow-up study.

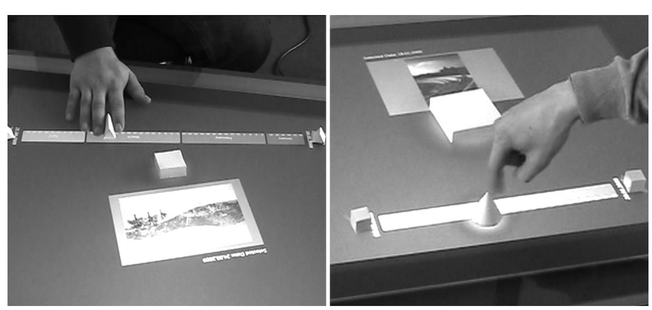

Fig. 6. Designing a photo browsing application using *Paperbox* to explore variations of form factors in participatory design sessions.

Comparison

The questionnaire results contrasted users' opinions when prototyping with Paperbox vs. Post-it® notes (e.g., Fig. 7).

Considering the expected *communicational benefits* of graspable low-fidelity objects, the tangibility of the paper objects provided the advantage of *stimulating communication* (mode=3, see Fig. 7) and allowed the participants to *express* and *visualize* (mode=5, see Fig. 7) ideas for TUIs on interactive surfaces more quickly than when using the less physical means provided by Post-its®.

While the above study provided good initial support for *Paperbox*, we wanted to investigate the capabilities of our tangible prototyping method in a more real-world setting with real designers. Consequently, we took *Paperbox* to an industrial context, as presented next.

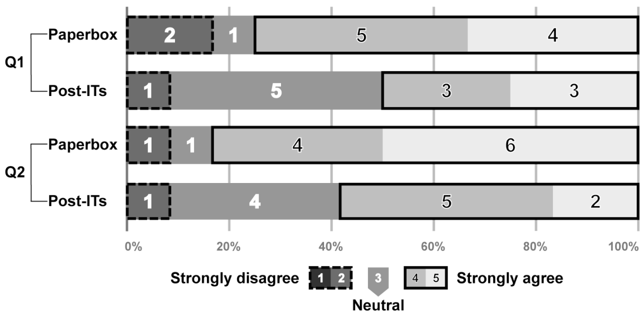

Fig. 7. Results of Q1: "The method facilitates communication" and Q2: "The method was suitable to express our ideas."

INDUSTRIAL USE CASE

A large manufacturer of consumer devices approached us to help them envision the design of a tangible user interface for their future products. In particular, the company's design team was confronted with the challenge of developing a physical interface atop a thin film transistor (TFT) display. The task was to create a control element atop an interactive display that would allow a user to set certain parameters, and to switch between different applications. The element would thus act as a multifunctional input device. For reasons of confidentiality, we cannot detail the actual type of device. Fortunately, that detail is not required to understand the analysis below.

We began by investigating their current design studio practices, expecting a variation of the extended interaction design process as shown in Fig. 3. We learnt that their normal approach to designing new interface solutions involved creating various virtual 3D renderings. They would then present those renderings to other internal members. Decisions would be made, including which of the generated concepts would be turned into high fidelity physical prototypes. They would pass these on to a model-maker and receive a physical, non-interactive version of their favored design. Finally, they would add additional electronic components to emulate interactivity, but only in a very rudimentary way. As seen in this process, the physical manifestation appeared only late in the process.

We offered our toolkit as a starting point for extending their design process. By using our toolkit, the designers would: (1) brainstorm various interface concepts with the aid of *Paperbox*, and (2) physically express the ideas early in the process while simultaneously exploring form factors and interactivity. We suggested that the design team could then select their favored interaction concept and create representations on higher fidelity levels while simultaneously conducting tests with users to improve the concept and the usability of the interface.

Our study setup investigated the use of *Paperbox* from several different viewpoints:

(1) We observed the designers. At key points in the design process (e.g., when a prototype was recreated at a higher fidelity) we conducted expert interviews. We asked them about their experiences with the *Paperbox* process, and any limitations they saw within it.

(2) Potential end users of the interface participated in usability inspections. We invited test subjects to judge if our approach could be also utilized for user testing.

(3) We recorded our personal observations of the design process over time via diaries.

Expert Interviews

The expert interviews were undertaken at four points during the design process. Following an iterative design process (see Figure 3), the fidelity of the prototype in question was constantly increased towards a high-fidelity representation.

Setup and Participants

We individually interviewed seven experienced designers; all were employees of the same design studio (3 female, average age was 34 years). Four were employed as senior industrial designers, two were graphic designers and one was a design manager. Two of the participants were junior industrial designers. Each session lasted 45 minutes in total and was videotaped for later analysis.

Data and Analysis

Observations were accompanied by two questionnaires consisting of open questions and questions answered on five-point Likert scales. We conducted a semi-structured retrospective interview on what they thought of the design process. During this, participants were also asked to rate the suitability of a given prototype for certain (design) activities on a five point Likert scale, ranging from 1 meaning "strongly disagree" to 5 meaning "strongly agree."

The interview and questionnaire primarily probed the designers' evaluations of our implementation, emphasizing specifically the varied purposes and activities during various stages of the design process (Figure 3). The questions we asked therefore addressed their experiences with the toolkit (see Figure 2 & 4) and their perception of the created prototypes' *suitability* for:

- Brainstorming.
- Exploring variations of an interaction concept.

- Explorations on form factors.
- Investigating materiality aspects.
- Judging industrial design matters.
- Investigating the users' experiences (UX).
- Presentation purposes.
- Usability tests.

Findings

When analyzing the completed questionnaires, we discovered that the majority of the interviewed participants considered *Paperbox* to be a "...valuable extension..." for their internal design processes. The majority of the participants (6 of 7) appreciated the ability to create a variety of interactive prototypes rapidly in a difficult design context (see Figure 8).

The data also indicated that the majority of the designers considered *Paperbox* to be a brainstorming support tool that allowed for the exploration of interaction concepts as well as form factors in early stages of development. However, they also suggested that our implementation would only be useful for initial explorations during the brainstorming and concept development phases. They probably would not, for example, use the toolkit for presentation purposes (see Figure 8). Instead, the majority (6 of 7) of the interviewees stated that they would prefer to move on to a higher fidelity once a design concept has been agreed upon. In the following section we give a summary on these important points in greater detail.

Brainstorming and Concept Development

For the first two questions, we wanted to investigate the suitability of *Paperbox* for early process activities such as brainstorming and concept development. We considered these two idioms separately as we tend to think of the brainstorming phase as a stadium in which *any* idea may be valid, while ideas discussed in the concept development phase undergo a more systematic, strategic filter to evaluate the initially generated ideas and turn them into realistic concepts on an application level.

Regarding the suitability of *Paperbox* to brainstorming, five out of seven participants opted for "strongly agree" (see Figure 8). One designer simply "agreed" and the design manager remained "neutral" on this question. As recorded in a number of answers to the open questions and in our diary, the majority of participants stated that a prototype created with the prototyping toolkit was perceived as being *suitable* for these purposes. A similarly positive response frequency was received when we asked the participants if they would consider the toolkit to be a means of exploring interaction design concepts on a more detailed application level, as is represented in Figure 8.

Form Factors

During the design process, we aimed at supporting the core design activity of early form factor exploration. Six out of seven participants expressed a positive outlook (three "strongly agreed" while another three simply "agreed") on the toolkit's suitability to explore the physical shape of the control element (see Figure 8). One participant "disagreed" and stated that, in his opinion, this had only been possible in a "...very rudimentary way...".

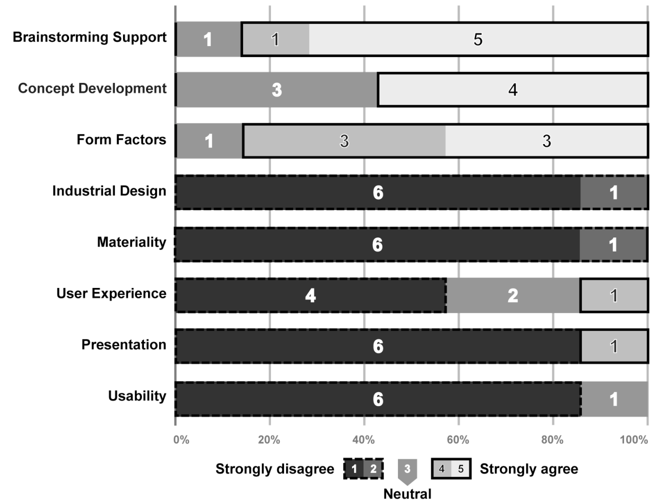

Fig. 8. The results of the Likert-Scale questionnaire on the extent to which the interviewed designers considered the use of *Paperbox* for different purposes during the design process.

In an additional question regarding the suitability of *Paperbox* for exploring form factors, all interviewed participants "agreed" (2) or "strongly agreed" (5) that the low fidelity prototype created with the toolkit was perceived as being appropriate for this task (see Figure 8).

Materiality and Industrial Design Matters

Reflection on materiality is a core activity within industrial design practices. While we explicitly highlighted the exclusion of these aspects during early phases of the process, as they would provoke unwanted feedback, we wanted to know if the participants would consider the usefulness of the toolkit for this purpose at any given point during the whole process (e.g., in later phases). We received very distinct feedback regarding this matter as six participants "strongly disagreed" and one "disagreed" that the prototypes created with the toolkit would stimulate ideas regarding the materiality of a graspable control element. They attributed this lack of suitability to the ambiguous nature of the toolkit, a nature that would not support *committal* design decisions (see Figure 8).

User Experience

One important factor for user acceptance of a new system is the experience (as understood by Hassenzahl [8]) it creates in actual use. We asked the designers if they thought that the toolkit supported the initial decision-making phase regarding user experience aspects. The feedback here was quite different than for other aspects (e.g., "presentation" or "materiality"). Four out of seven designers "strongly disagreed" that a prototype created using *Paperbox* would support explorations in this realm, while one participant "agreed" and two remained "neutral" (see Figure 8).

Presentation

Prototype creation in large companies, as in our context, is mainly undertaken to introduce other people (e.g., product managers, CEOs, etc.) to the design concept in the setting of a formal presentation. As we observed, the overall work goal of the design team was to present their concepts to product managers and get them approved, thus turning their ideas into a marketable products. In the light of these goals, we asked the participants if they would use the created prototypes in these presentations. As Figure 8 indicated, six of seven participants "strongly disagreed" and did not consider *Paperbox* to be suitable for presentation purposes, while only one participant "agreed." The majority of the interviewed designers would use the *Paperbox* prototype (5 of 7) "...only within the developing team in order to make early decisions..." One participant expressed that, "...they (the created prototypes) look too premature to present."

Usability

In the final question of the expert interview study we focused our attention on the probability of the participants using the prototyping toolkit for early usability measurements. Six out of seven participants "strongly disagreed" and one "disagreed" that the resulting prototypes would be suitable for usability inspections (see Figure 8). They assumed that invited users would not have the necessary ability to *see beyond* the cardboard and that the prototypes would lack the appropriate accurateness for testing purposes. In their opinion users would "...rate the system's usability negatively as a consequence...".

Summary: Findings and Open Questions

The results of the study shows that the introduction of a TUI framework into an industrial setting is subject to strong constraints that need to be considered to make the approach successful in practice. We were surprised that the design experts had objections to using low-fi TUI prototypes for usability testing, in particular as in traditional UI design paper prototyping has become widely accepted. The results might hint at the necessity to more clearly define the role of cardboard prototypes in TUI design in terms of the benefits and limitations and the kinds of user tests that can be performed with such low-fidelity prototypes. It seems that in traditional UI design, designers are well aware of the limits of paper prototyping as a technique. The additional feedback we received from the design experts is summarized in the following bullet lists. Direct feedback to the open questions mainly addressed the perceived benefits and limitations of the toolkit:

Benefits:

- Fast, cheap and easy to build.
- Capable of visualizing the interface.
- Helpful for initial prototyping.
- Well-suited brainstorming tool.
- Excludes details.

Limitations:

- Not presentable due to unfinished design.
- Limited suitability for usability studies.
- Not very accurate (precision is crucial to measure user experience [3, 8]).

Despite these findings we wondered whether our designers' judgments of the limited suitability for usability studies were accurate. One of our initial assumptions had been that the envisioned interaction concepts, prototyped with *Paperbox,* would allow early usability measurements. The initial answers of our respondents, on the other hand, represented opinions rather than first-hand experience. We therefore undertook a formal usability inspection using prototypes created with the aid of our toolkit and compared the results with prototypes on higher fidelities (see Fig. 9).

USABILITY INSPECTION

The exploratory usability tests we conducted with potential end-users were aimed at investigating the feasibility and practicality of usability tests with low-fidelity artifacts created with *Paperbox*. More specifically, we examined whether the artifacts would deliver data that could help in improving usability.

Participants and Setup

Our study was a between-subject design involving 36 participants (12 female, average age was 25 years). All participants were students of different disciplines from a large university.

We developed three prototypes of different fidelity levels as our testing mediums (see Figure 9). The coupled digital interface representation incorporated four value counters ranging from 0-9 that could be selected by *tapping* on the physical interface in a spot next to the displayed value (see Figure 9, left). When a value counter was selected, it would respond to the rotation of the TUI by increasing the value through clockwise rotation and decreasing the displayed value through anti-clockwise rotation.

The individual test sessions were conducted as follows. First, participants were provided with a single prototype at a given fidelity level (i.e., the between-subjects design). Next, participants received a 5-minute introduction to (a) the overall context of the study and (b) a brief introduction to the prototypes' features. Third, participants were asked to carry out two tasks, both of which were considered to be typical use cases for the product line in question, and which were suggested by the industrial partner.

- **Task 1:** Place the TUI on a capacitive sensing device (an iPad). Starting from value "0", set the appearing pie menu to the value "9" through clockwise rotation.
- **Task 2:** Set the value of the first interface representation back to "3", then switch to another value counter and set the value of the second counter to "8".

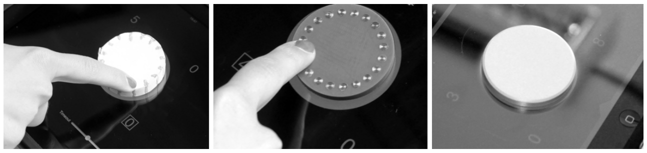

Fig. 9. Prototypes of three fidelity levels as a means for usability studies: prototype (1), created with cardboard and conductive ink (left), a functional mid-fidelity prototype (2) (middle) and a glazed high-fidelity prototype (3) (right).

Finally, after the participants had performed the two tasks using one out of three prototypes, they were asked to fill out a questionnaire on their usability satisfaction consisting of 7-point Likert-scale questions, ranging from "1" meaning "strongly disagree," to "7" meaning "strongly agree" combined with additional open questions. The questionnaire was based on the psychometric evaluation for computer usability studies, initially presented by Lewis [12].

Data and Analysis

We observed the testing sessions using the human behavior research system *Observer XT 10.5*[2]. We designed a coding scheme using this system to track task completion time, errors, and communication of the participants. The following aspects were observed and documented during the study:

- Completion time for task 1.
- Completion time for task 2.
- Feedback referring to the different prototypes.
- Ratings in the After-Scenario-Questionnaire.

All participants were also recorded on video for later analysis, and additional photographs of the setup were taken.

Findings

We measured completion time in order to judge in how far low-fidelity prototypes could be used as an effective means of accomplishing a given task in a *reasonable* amount of time. To investigate what time frame the participants perceived as *reasonable* we employed a Likert scale question in the follow-up questionnaire.

The prototypes created with *Paperbox* were limited in their construction, especially compared to their mid- and high-fidelity counterparts, and thus their performance was expected to be lower. The toolkit-created prototype's (Prototype 1) main shortcoming was that it did not have a fixated rotation axis as the other, more refined versions did (Prototypes 2 and 3).

As Figure 10 shows, the *Paperbox* prototype confirmed our initial assumptions and its performance was inferior in Task 1 with 8.65 seconds on average, (SD 2.71) while prototype 2 had 6.56 seconds on average (SD 3.18) and prototype 3 had 6.41 seconds on average (SD 3.22). The difference was the result of the aforementioned limited accurateness of the

[2] www.noldus.com

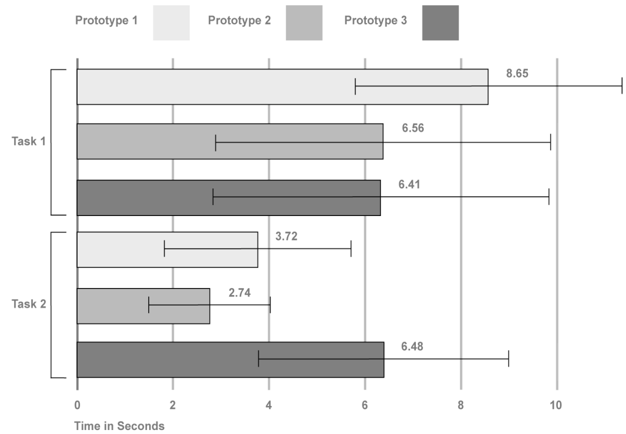

Fig. 10 Results of the explorative usability study, time measurements for completing Tasks 1 and 2.

paper object. Yet the practical significance in the two second differences between prototypes is likely small. Indeed, answers provided in the follow up questionnaire did not express a negative perception of the interaction experience (see Figure 11). In fact, the *Paperbox* prototype received positive response frequencies (mode=6) similar to the other higher fidelity versions (see Figure 11).

Prototypes 2 and 3 received similar values accomplishing Task 1 (see Figure 10), which was a result of their similar technical configuration: the attached rotation mechanism allowed for a very precise rotation.

Regarding task 2, it took the participants an average of 3.72 (SD 1.80) seconds using the *Paperbox* prototype. The mid-fidelity prototype performed best as it took the participants an average of 2.74 seconds (SD 1.39) to complete, while the positive response frequency was additionally the highest in the follow-up questionnaire (see Figure 11).

Surprisingly, the high-fidelity prototype performed worst with an average task completion time of 6.48 seconds (SD 2.60). This resulted from a technical limitation: the glazed paint decreased the conductivity slightly and caused difficulties in half of the experiments, particularly when the participants *switched* between different value counters.

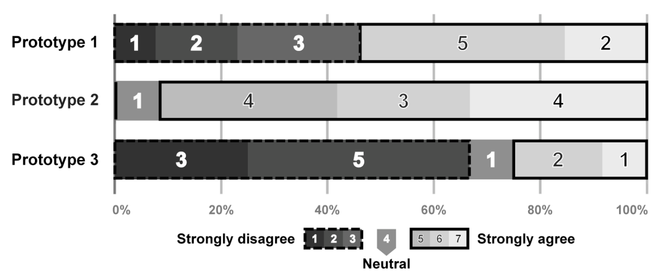

Fig. 11. Response frequencies to the prompt "The physical prototype allowed me to accomplish the given tasks in a reasonable amount of time."

Users who did not apply a certain amount of "pressure" did not receive immediate feedback and felt that the system did not respond correctly. This issue affected also the prototype's rating in the questionnaire, indicated by the low scores (mode=2) prototype 3 received, (see Figure 11).

Regarding the perceived *ease of use,* prototypes 1 (mode=6) and 2 (mode=5 and 6) received higher positive values than prototype 3 (see Figure 12). The scores of prototype 1 reflects a disparity with the statements made in the expert interviews, in which the design team did not consider a *Paperbox* prototype on this fidelity level to be suitable for conducting early usability tests.

The large number of negative responses received by prototype 3 (mode=2) was again due to the aforementioned technical difficulties occurring only at one point during task 2.

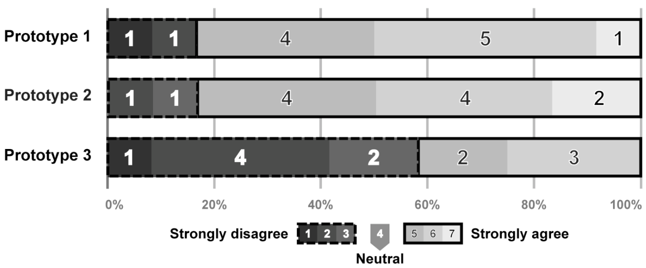

Fig. 12. Response frequencies to "It was easy to accomplish the given task using the provided physical prototype."

After the two trials were completed, we asked participants how they perceived the overall usability of the proposed system, and if they felt that the interface would provide *enough* information to accomplish the given tasks. All prototypes received more positive scores than negative (see Figure 12).

These scores indicate that in all three conditions the majority of the users found that the overall interface provided enough information to accomplish the given tasks. The equal distribution of the scores (all prototypes received 7 scores in the range of 5-7) indicates that the participants expressed their experiences with the different prototypes in the two previous responses and did not deal with the interface concept per se, as in case of the final question (see Fig. 13).

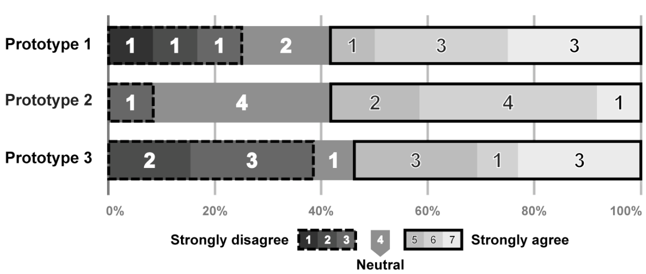

Fig. 13 Response frequencies to the prompt "The physical prototype and the displayed graphical interface provided enough information to accomplish the given task."

Summary

This exploratory usability study supports our theory that even low fidelity mockups made of paper and conductive ink can be used to detect usability issues. The low-fi prototypes created through *Paperbox* allowed users to accomplish given tasks. They performed *relatively well* when compared with their mid- and high-fidelity counterparts. While task completion time was somewhat slower with *Paperbox*, users did not perceive this as negatively affecting their interaction experience. Thus, our results contradict the design experts' opinions from our second study: prototypes created on low fidelities *can* serve for usability testing purposes and as an aid for the user-centered design process of tangible interaction.

The implementation issue in our third prototype deserves additional discussion. On one hand, it did negatively affect user performance, and can be seen as a flaw in our study. On the other hand, it reflects the problem of increasing fidelity too soon: users are exposed to problematic production details that may confound their experiences. As others have noted repeatedly in paper sketches, low fidelity sketches are often preferred over high fidelity ones in early design as they encourage users to respond to the concept rather than to unimportant details. We believe the same is true for physical prototypes.

DISCUSSION AND CONCLUSIONS

We presented a toolkit and an approach for designing tangible interactions using low-fidelity physical shapes to explore different form factors. Our approach is replicable, as we have made the prototyping toolkit publicly available online. Our repository includes: (a) templates for building the physical artifacts, (b) clear instructions on the techniques and hardware presented, and (c) the source code necessary to install the created applications on capacitive sensing devices. We have demonstrated the practical use of our implementations through case studies with both student designers and with an industrial partner. We explored the usefulness of our approach through repeated expert interviews and usability tests with potential users.

Paperbox can be used immediately as a system. However, as a philosophy, it also extends the design process and advocates a strong role for early low-fi physical prototypes in graspable interfaces.

Nevertheless, we recognize that higher-fidelity prototypes also serve an important role. The use of the *Paperbox* toolkit in an industrial setting uncovered several unexpected points. Prototypes in industrial design settings often seem to serve very specific purposes beyond design elaboration, such as convincing management to productize a certain design. These forces and constraints need to be understood better in order for a prototyping method to be successful in real design studios.

We need to better understand the scope and applicability of all available prototyping frameworks in terms of their strengths and limitations – something that has already been achieved for paper prototyping of traditional UIs. In addition, designers may have biases based on how they currently do things vs. how they could do things. Thus we would have to convince practitioners in physical design that low-fi physical prototyping is worthwhile: it allows quick and cheap exploration of the many design alternatives that are the basis of successful designs.

Finally, we recognize that *Paperbox* is only a beginning. Its current version fully relies on low-fidelity paper templates that can be downloaded and constructed by anyone. However, there is no reason why we need to limit it to paper in general. For example, it would be relatively cheap to manufacture physical building blocks that resemble the *Paperbox* elements. Depending on their purpose, these could appear as rough wooden blocks, as polished metal, or even containing paintable surfaces. They could also include embedded conductive magnets (to ease creation of compound objects) and pre-configured conductive parts for capacitive sensing.

GUI interface designers have a multitude of sketching tools and media to choose from. The same is not yet true for TUI designers. *Paperbox* is a starting point in this direction.

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References

1. Avrahami, D., Hudson, S.E. Forming interactivity: a tool for rapid prototyping of physical interactive products. *In Proc.* DIS '02. 2002
2. Biederman, I. Recognition-by-components: A theory of human image understanding. Psychological Review. *American Psychological Association,* 1987
3. Buxton, B. Sketching User Experiences: Getting the Design Right and the Right Design. *Morgan Kaufmann*, 2007.
4. Eisenberg, M. Output devices, computation, and the future of mathematical crafts, International Journal of Computers for Mathematical Learning. *Kluwer Academic Publishers*, 2002.
5. Eisenberg, M., Eisenberg, A., Hendrix, S., Blauvelt, G., Butter, D., Garcia, J., Lewis, R., Nielsen, T. As we may print: new directions in output devices and computational crafts for children. *In Proc.* Interaction Design and Children'03, 2003.
6. Greenberg, S., Carpendale, S., Marquardt, N., Buxton, B. Sketching User Experiences: The Workbook. *Morgan Kaufmann Press*, 2012.
7. Greenberg, S., Fitchett, C. Phidgets: easy development of physical interfaces through physical widgets, *In Proc.* UIST'01, 2001.
8. Hassenzahl, M., Diefenbach, S., Göritz, A. Needs, affect, and interactive products–Facets of user experience, Interacting with Computers. *Elsevier*, 2010.
9. Hornecker, E. Beyond Affordance: Tangibles' Hybrid Nature. *In Proc.* TEI '12, 2012.
10. Ishii, H. Tangible bits: beyond pixels, In Proc. TEI'08, 2008.
11. Ishii, H., Ullmer, B. Tangible bits: towards seamless interfaces between people, bits and atoms, *In Proc.* CHI '97, 1997.
12. Lewis, J.R. Psychometric evaluation of an after-scenario questionnaire for computer usability studies: the ASQ, *In SIGCHI Bull,* 1991.
13. Norman, D.A. Affordance, conventions, and design. *Interactions*, 1999.
14. Rekimoto, J., Ullmer, B., Oba, H. DataTiles: a modular platform for mixed physical and graphical interactions, *In Proc.* CHI'01, 2001.
15. Sanders E., William, C. Harnessing people's creativity: Ideation and expression through visual communication, *Focus groups: Supporting effective product development*, 2001.
16. Shaer, O., Hornecker, E., Tangible User Interfaces. *Now Publishers Inc.* 2010.
17. Snyder, C. Paper Prototyping: The Fast and Easy Way to Design and Refine User Interfaces. *Morgan Kaufmann,* 2003.
18. Ullmer, B., Ishii, H. The metaDESK: models and prototypes for tangible user interfaces, *In Proc.* UIST'97, 1997.
19. Wiethoff, A., Schneider, H., Rohs, M., Butz, A., Greenberg, S. Sketch-a-TUI: low cost prototyping of tangible interactions using cardboard and conductive ink, *In Proc.* TEI'12. 2012.