FrameBox and MirrorBox: Tools and Guidelines to Support Designers in Prototyping Interfaces for 3D Displays

Nora Broy[1,2,3], Stefan Schneegass[3], Florian Alt[1,3], Albrecht Schmidt[3]

[1]University of Munich
Media Informatics Group
Amalienstraße 17
80333 Munich, Germany
firstname.lastname@ifi.lmu.de

[2]BMW Group
Research & Technology
Hanauer Straße 46
80992 Munich, Germany
Nora.NB.Broy@bmw.de

[3]University of Stuttgart
VIS
Pfaffenwaldring 5a
70569 Stuttgart, Germany
firstname.lastname@vis.uni-stuttgart.de

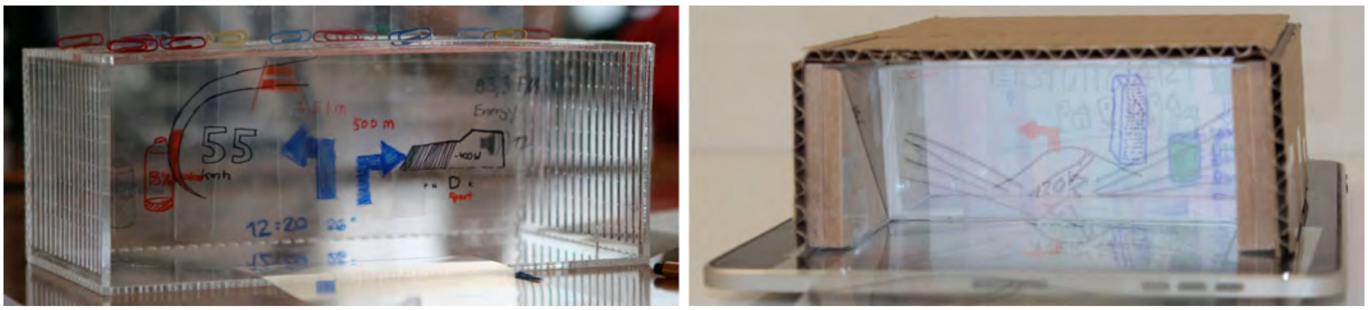


Figure 1: We present two tools for stereoscopic 3D (S3D) user interface prototyping: The FrameBox (left) is made of laser-cut acryl and allows for inserting UI elements painted on transparency films into several slots (x and z position). Paper clips can be used to adjust the y position. The MirrorBox (right) uses semi-transparent mirrors to reflect UI elements painted on transparency films. An iPad is used as a backlight.

ABSTRACT
In this paper, we identify design guidelines for stereoscopic 3D (S3D) user interfaces (UIs) and present the MirrorBox and the FrameBox, two UI prototyping tools for S3D displays. As auto-stereoscopy becomes available for the mass market we believe the design of S3D UIs for devices, for example, mobile phones, public displays, or car dashboards, will rapidly gain importance. A benefit of such UIs is that they can group and structure information in a way that makes them easily perceivable for the user. For example, important information can be shown in front of less important information. This paper identifies core requirements for designing S3D UIs and derives concrete guidelines. The requirements also serve as a basis for two depth layout tools we built with the aim to overcome limitations of traditional prototyping when sketching S3D UIs. We evaluated the tools with usability experts and compared them to traditional paper prototyping.

Author Keywords
Prototyping; Stereoscopic 3D; User Interfaces

ACM Classification Keywords
H.5.2 User Interfaces: Prototyping

INTRODUCTION
3D displays are nowadays widely available for entertainment in cinemas or home environments. While the need for glasses is likely to be a major hindrance for their uptake, we believe that the advent of auto-stereoscopy leads in the near future to 3D displays becoming ubiquitous, for example in mobile phones, public displays, and cars. This provides novel means for designing user interfaces and exploiting the third dimension, including the opportunity to present information on different depth layers. Prior work shows that depth combined with other salient cues (e.g., color, motion) can improve the performance of visual search tasks [1, 8]. For instance, frequently used applications on mobile phones could be grouped together, using depth as an indicator for the most recently launched application. In security-critical environments, like the automobile, where users need to be able to quickly and accurately perceive information, a comprehensive visual structure can help to immediately identify important information.

To build such interfaces, there is an increasing need to provide basic design guidelines to sketch and arrange graphical user interface (GUI) elements. Building such S3D interfaces is in many ways challenging. For example, designers need to cater to the fact that elements cannot equally be perceived in different locations in 3D space and that a minimum distance needs to be maintained between elements so that users can easily distinguish which element is shown further to the front [4]. Hence, this paper puts a strong emphasis on understanding how the user can be supported in prototyping successful and usable S3D interfaces.

To do so, we identify requirements for layering information in 3D space. We study related literature and complement our findings by conducting a laboratory study which investigates object arrangement on different depth layers. We found that (a) positioning information on more than six layers significantly decreases user performance for depth-related search tasks; (b) that grouping objects can reduce error rates and task completion times for depth-related search tasks; and (c) that maximizing the distance between layers improves user performance when distinguishing information on different depth layers. These findings, together with the results from related work, serve as a holistic foundation to understand the requirements of layered S3D UIs.

At the same time, tools are needed that provide means to arrange items in 3D space. Within the field of user-centered design, low-fidelity prototyping is a powerful means to quickly and easily prototype new interfaces. Well-established techniques such as paper prototyping, however, cannot easily be adopted for S3D UIs as they do not support the positioning of UI objects in 3D space. As a solution we report on the design and development of two depth layout tools for prototyping S3D UIs. The design of the MirrorBox and the FrameBox (Figure 1) was informed by many of the requirements identified in the first part of our work.

We evaluate the prototypes and the generated guidelines in the context of two concrete use cases – S3D mobile phones and S3D dashboards in cars. Feedback from expert users suggests that the proposed prototyping tools are superior to ordinary paper prototyping as they encourage observation of the collected guidelines, support collaboration, and increase creativity as well as the perceived fidelity.

The contribution of this paper is threefold:

- First, we describe requirements for the design of layered S3D UIs, based on a literature review and a lab study.
- Second, we report on the design and development of the prototyping tools FrameBox and MirrorBox.
- Third, we present findings from an evaluation of the prototypes and guidelines by means of two expert focus groups.

RELATED WORK

In this work, we focus on interfaces for S3D displays. In general, the term 3D user interface is related to spatial input [3] and less to the graphical output of the UI. Therefore, we use the term S3D user interface to emphasize our research interest concerning the depth layout of the UI's visual output. We revisit related work from other application areas on 3D displays and provide an overview of prototyping tools.

S3D User Interfaces

3D displays are becoming increasingly popular as traditional 2D displays are being replaced by their 3D counterparts. They are deployed in a variety of contexts (e.g., mobile phones or laptops). Prior work explored the benefits of S3D displays. A detailed review of the performance benefits of S3D is presented by McIntire et al. in [15]. In the field of mobile phones, S3D displays increase UX [6, 26]. Broy et al. propose a concept for enhancing menu structures of a car infotainment system with S3D [5]. They show that the S3D presentation is more compelling and comprehensive than the 2D version. Prior work also shows how to use the third dimension for information visualization. In particular, it is used for medical applications [28], CAD tools [16], gaming [14, 21], as well as for navigation in virtual environments [3].

Prototyping

Prototyping constitutes an important step in the user centered design process of graphical user interfaces to build usable systems. It is applicable in different stages of the design process, ranging from early sketching on paper (low fidelity) to an almost implemented product (high fidelity) [20].

Prototypes, particularly in the early stage of designing UIs, are an important way to communicate and discuss ideas and requirements [2]. For this purpose, paper prototyping is often used as one of the most popular techniques. Snyder defines paper prototyping as a method of brainstorming, designing, creating, testing, and communicating user interfaces [24]. Due to the convenience of this approach, people at all stages of the development process and with diverse backgrounds can participate in the process, including designers, usability engineers, programmers, and end users.

As a system matures, increasing fidelity helps to improve the validity of evaluation through preliminary user studies [13]. Software toolkits have been developed for diverse application domains, including ubiquitous computing environments [13], location-aware applications [12], or mobile projectors [30]. In addition, hardware toolkits [11, 22] have been developed to rapidly prototype interactive devices and tangible UIs.

Discussion

The variety of application areas for S3D UIs shows the potential regarding tools for prototyping 3D depth layouts. Engaging interfaces that extend beyond straightforward user perception activities can particularly benefit from these tools. In particular, we see large potential in considering core challenges in S3D UI design and addressing them via tools that guides users during the design process. In the following, we present a requirements analysis before reporting on the development and evaluation of the tools proposed in this work.

LAYERED 3D - EXPLORING REQUIREMENTS

At the outset of our work, we aimed to understand fundamental challenges that affect the design of feasible S3D UIs. Previous work uncovered a number of aspects related to content design that strongly influence the quality of S3D UIs. In the following, we collect guidelines from previous work to facilitate design decisions for high quality layered S3D UIs.

Comfort Zone: Prior work found that excessive parallaxes reduce the viewing comfort due to accommodation and vergence mismatches [10]. Hence, a comfort zone needs to be determined in which it is easily possible for the user to perceive information. As a rule of thumb, Lambooji et al. recommend limits for retinal disparities of 1° with respect to Panum's fusion area [10]. However, there are studies that reveal more conservative values (e.g., [31]).

Show Content Behind the Screen Layer: Prior studies recommend the use of positive disparities for information display. Hence, the main content should be positioned behind the screen. Negative disparities can cause longer task completion times [4] and visual discomfort [14, 19].

Minimal Distance: Stereoscopic depth is a super acuity which allows a depth difference assessment of 40 arc-sec. Broy et al. explored the minimal distance between two depth layers that allows for quick separation [4]. They suggest a threshold of 2.7 arc-min.

Careful Use of Monocular Depth Cues: Monocular depth cues can support the spatial impression of stereoscopic visualizations, particularly in virtual environments [14]. However for abstract content (e.g., icons) that is likely to appear in layered information interfaces, monocular depth cues should be applied carefully so that scenes do not become unnecessarily complex, for example, through shadows. Moreover, focal blur can reduce user performance in judging depth and perceived quality of the system [17].

Use of Text: It is advisable to display text parallel to the screen surface, since perspective distortions reduce readability. Stuerzlinger et al. found a sharp decrease for rotations larger than 60 degrees [25].

Highlight Objects by Combining Salient Cues: Combining salient features for highlighting objects has been shown to decrease search times [1, 8]. Hence, S3D UIs should employ a foremost layer that depicts urgent information, such as warnings and notifications.

In summary, our analysis of prior work provided us with a rich set of requirements that we used to inform the design of our depth layout tools. The complex nature of S3D UIs suggests that the tools should be able to guide the user towards the optimal UI design process. At the same time, they help us to create guidelines for layered S3D UI design. However, there is a considerable lack of knowledge on how to structure and group information presented in 3D space, which is crucial for creating UIs for 3D displays [29]. Hence, we aim to close the gap through the subsequent user study.

STRUCTURING INFORMATION IN S3D UIS

We conducted a user study to evaluate how information can be structured and grouped in a 3D layered UI. In particular, we are interested in user performance when identifying grouped objects on one depth layer while several other (distractor) layers are present. We investigate how the number of layers, the distance between those layers, and the x- and y-distance between grouped objects impact task completion times and error rates for a depth-related search task. For this search task, participants have to identify two related objects among several distractor objects. The relation between the objects is defined by their depth position, meaning that objects on one depth layer belong to one group.

We investigate the following hypotheses:

H1: Smaller numbers of depth layers increase user performance in identifying grouped objects via depth.

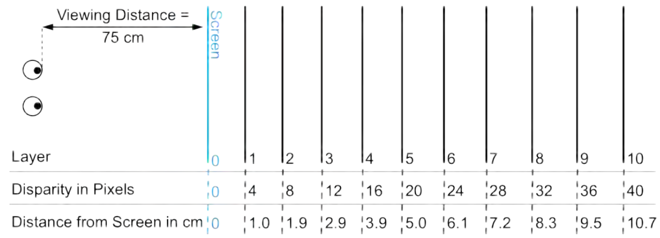


Figure 2: Layer positions applied in the user study. The distances between the screen layer and each depth layer are given in pixels and cm.

H2: Grouping objects additionally via x and y axes reduce error rates and task completion times for a depth-related search task.

H3: By increasing the distance between depth layers, user performance also increases.

Apparatus

For presenting information layers with different depth positions, we employ the 3D display of a notebook equipped with NVIDIA 3D Vision 2 shutter technology. We use a resolution of 1280x480 on a diagonal of 10.5". As a depth range we use parallaxes up to 40 pixels and as a minimum distance between two depth layers we use 4 pixels, as has been suggested by prior work [4]. According to Mahoney et al., information presentation should focus on the area behind the screen [14, 19]. Hence, we do not consider negative parallaxes in our study. Figure 3 visualizes the examined positions for the depth layers. The values are calculated with respect to our setup (pixel pitch = 0.196; viewing distance = 750 mm).

As we foresee text and icons to be important parts in informative UIs, we use binocular disparity as depth cue to structure information. In contrast to monocular cues (relative size, shadows, lighting, occlusion), binocular disparity neither changes the size of object (which is important for readability) nor does it make parts of the scene invisible.

Tasks

The participants had to solve two tasks during the experiment. First, we use a depth-related search task to gather insight into user performance when deciding on depth relationships between objects presented with the 3D display. We presented one object labeled with a number on each depth layer and, in addition, a reference object on one of the depth layers, showing a red square (Figure 3). The task for the participant was then to find the object placed on the same depth layer as the reference object (we refer to this also as the target object). All objects were squares with a height and width of 90 pixels. Note, that due to the lack of monocular depth cues it is not possible to identify the target object in Figure 3–top. For the purpose of simplicity, we rendered the scene in a 3D perspective (Figure 3–bottom).

Second, a distractor task prompted the participant to switch their visual focus to a large distractor display placed behind the 3D display. We applied the additional distractor task to increase the difficulty of the depth-related search task and to satisfy requirements for real world applications that involve

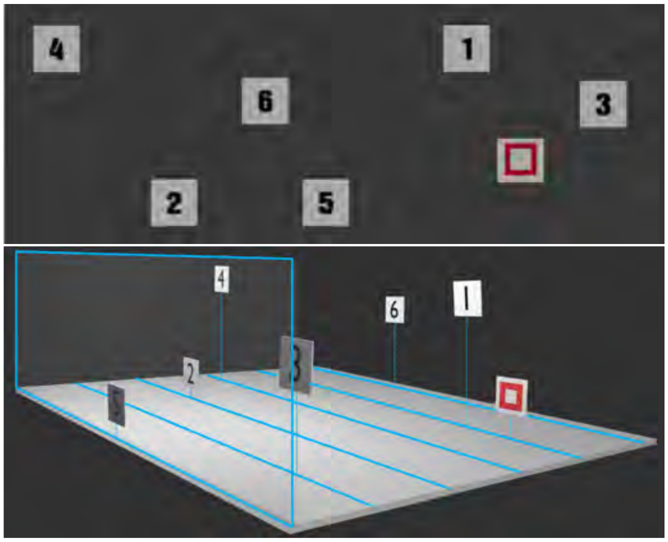


Figure 3: The search task in front view (top) and perspective 3D (bottom). In this example, the numbered squares occupy six layers while the reference object is located at the same depth layer as object *1*.

accommodation switches commonly occurring in pervasive display environments (e.g., automotive or mobile applications). The distractor task required the participant to focus and read a word depicted on the distractor display aloud. The words are composed of two or more simple, unrelated nouns (e.g., *daybreakhazard*) that force the participant to focus cognitively and visually on the distractor display.

Study Design

The study was designed as a repeated measures experiment. We altered three independent variables:

Depth Layers: We expected that the number of depth layers impacts user performance. Since one object is shown on each layer, we assumed that higher numbers of depth layers decrease user performance. Therefore, we tested the impact of 4, 6, and 8 layers.

XY-Distance: Based on the law of proximity, we expected effects on user performance for varying x- and y-distances between the target and reference object. We investigated small (5-15% of the screen‘s diagonal), medium (35% - 45%), and large distances (65% - 75%) for this study.

Z-Distance: The distance between two layers can be maximal (the layers are linearly distributed within the depth budget) or minimal (the layers are distributed 4 pixels next to each other starting with the screen layer). We thought that the z distance impacts the user performance.

Beside these independent variables, the depth position of target and reference objects can have a potential influence on user performance. Hence, we tested every possible layer position for target and reference square over all conditions. This resulted in (4*3*2) + (6*3*2) + (8*3*2) = 108 depth judgment tasks that every user has to solve. We grouped the conditions by blocks of depth layers. To avoid sequence effects

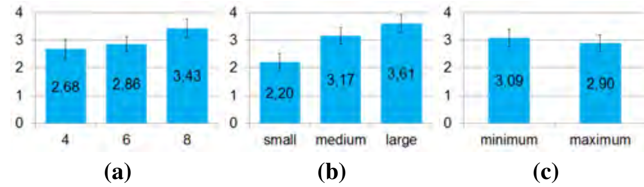


Figure 4: TCT mean values and standard errors as error bars for (a) depth layers, (b) xy-distance, and (c) z-distance. An ANOVA shows significant main effects for depth layers, xy-distances, and z-distance.

we counterbalanced the presentation of these blocks. The order of the xy- and z-distance conditions was randomized for each block. We measured task completion times (TCT) and recognition rates (RR) for the depth judgment task. Beside these objective measurements, the users rated the perceived difficulty of the task.

Recruiting, Setup, and Procedure

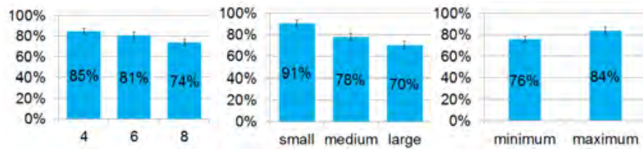
For the conducted study we recruited 30 participants through mailing lists. As participants arrived they were briefed on the study purpose and procedure. Prior to the study, we tested visual acuity with a Snellen test [23] and stereo vision with Random Dot Stereograms (RDSs) [9]. Participants passing both vision tests qualified for the study. They proceeded by completing a demographic questionnaire. Afterwards, the participants were seated 75 cm in front of the shutter display and 200 cm in front of the distractor display, respectively. We used a chin rest to ensure the same viewing distances across conditions and participants. After a training session (12 tasks), the participant started with the first task of the respective depth layer block by pressing the space key on the provided keyboard. After the participants detected the target object, they pressed the space key and read aloud the number shown on the target object. The difference between these button press events was measured as TCT. Next, the participant performed the distraction task. This procedure was repeated for all three blocks. After each block, the participants completed the questionnaire evaluating the difficulty of the task.

Results

In total, 30 participants (6 female, 24 male) aged between 20 and 53 ($M = 29.0$, $SD = 6.9$) took part in this study. All participants have normal or corrected to normal visual acuity and passed the stereo vision test.

Task Completion Time

Figure 4 shows mean and standard errors of TCT for depth layers, xy-distances, and, z-distances. We used a three-way analysis of variance (ANOVA) with repeated measures to investigate statistical differences. There are statistically significant differences for TCT concerning the number of depth layers, $F(2, 58) = 13.877$,$p < .001$,$r = .548$, the xy-distance between target and reference object, $F(2, 58) = 59.926$, $p < .001$, $r = .814$, and z distance between depth layers, $F(1, 29) = 4.361$, $p = .046$, $r = .317$. We used pairwise t-tests with Bonferroni corrections for post-hoc analyses. For the number of depth layers the t-tests reveal statistically significant effects between 4 and 8, $T(29) = -5.564$, $p \leq .001$,



(a) (b) (c)

Figure 5: RR mean values and standard errors as error bars for (a) depth layers, (b) xy-distance, and (c) z-distance. An ANOVA shows significant main effects for depth layers, xy-distances, and z-distance.

Depth Layers	Mean	Standard Deviation
4	3.567	1.612
6	4.067	1.388
8	4.500	1.614

Table 1: Means and standard deviations for subjective ratings of difficulty depended on depth layers. Difficulty was rated on a seven point Likert scale from one (very easy) to seven (very difficult).

as well as 6 and 8 layers, $T(29) = -4.242$, $p \leq .001$. The comparison of 4 with 6 layers is not statistically significant, $T(29) = -1.047, p = .911$. Concerning the xy distances, the pairwise t-tests reveal significant differences between all distances, all $p \leq .001$. The results show that the TCT depends on the number of depth layers, xy-distance, and z-distance between the depth layers.

Recognition Rate
Figure 5 depicts mean and standard errors of the recognition rate (RR) for depth layers, xy-distances, and, z-distances. Analyzing the RR, a repeated measures ANOVA shows statistically significant differences for the number of depth layers, $F(2, 58) = 20.486$, $p < .001$, $r = .628$, xy-distance, $F(1.687, 48.913) = 49.033$, $p < .001$, $r = .785$, and z-distance, $F(1, 29) = 30.230$, $p < .001$, $r = .702$. Mauchly's test shows that the assumption of sphericity is violated for xy-distance, $X^2(2) = 7.859$, $p = .02$, and, therefore, the degrees of freedom are corrected using Huynth-Feldt estimation of sphericity. In accordance to the results of TCT, pairwise t-tests with Bonferroni corrections show statistically significant differences for comparing 4 with 8, $T(29) = 6.475$, $p \leq .001$, and 6 with 8 depth layers, $T(29) = 4.090$, $p \leq .001$. Again, 4 versus 6 depth layers reveals no statistical significance, $T(29) = 2.263$, $p = .094$. Moreover, all pairwise comparisons of xy-distances are statistically significant, $p < .001$. Thus, the number of depth layers, the xy-distance, and the z-distance influence the RR.

Subjective Ratings
The participants rated the perceived difficulty of the depth-related search task after each depth layer block. The difficulty scale ranges from 1 (very easy) to 7 (very difficult). Mean values and standard deviations for the ratings after each depth layer block are listed in Table 1.

A Friedman test reveals statistically significant differences for the subjectively rated difficulty regarding the variation of depth layers, $X^2(2) = 13.640$, $p = .001$. Pairwise comparisons using Wilcoxon tests show significances between 4 and 6 layers ($p = .039$) as well as between 4 and 8 layers ($p = .006$). In general, participants state that it is easier to solve the task if the target and reference pair is placed at the foremost or backmost depth layer. Furthermore, the task is perceived as easier if no objects are located between the target and reference layer in terms of the object's x- and y-position on the screen.

Implications
The described study investigates the influence of the number of depth layers, their differences in depth as well as the influence of xy-distances for grouping and structuring information on depth layers. The results let us derive several implications facilitating design decisions for developing S3D UIs.

Information Layers
Our results show that an increasing number of depth layers decreases user performance in terms of TCT and RR. Moreover, the subjective ratings concerning the task difficulty support the findings. Therefore, we can accept hypothesis H1.

An explanation for this finding is provided by the Hick-Hyman law [7] (increasing the number of choices will increase the decision time) as well as the feature integration theory of Treisman [27] (combining features leads to a serial search meaning increasing distractor objects increase search time). However, Nakayma and Silverman found that the conjunction of two salient features with one being stereoscopic depth remains a parallel search [18]. The results of Nakayama and Silverman are based on two depth layers, meaning that each of the two layers allows for parallel search.

Our study shows that the decrease in performance is not statistically significant between 4 and 6 depth layers, although we observed a minimal performance decline. Hence, we assume that six information layers are still suitable for distributing information in 3D space, while 8 layers decrease user performance significantly. Based on these results, we recommend a maximum number of 6 information layers for designing a S3D layered UI.

Proximity in the Third Dimension
As our findings suggest, the xy-distance between objects plays a major role for grouping information via depth. As user performance significantly decreases for increasing xy-distance between target and reference object, we accept H2.

Therefore, we recommend using the entire depth budget behind the screen layer for information structuring. Besides a proper depth layer position of user interface elements, x- and y-locations have to be considered carefully. In general, the Gestalt psychology provides laws for grouping elements through specific characteristics. The law of proximity explains the performance reduction for increasing xy-distances and proves valid for the examined depth layers.

Moreover, we found that the law of proximity is also valid for the z-dimension. Maximizing the distance between depth layers within the comfort zone improves user performance. Hence, our study also confirms hypothesis H3. Nevertheless, this effect is absent for small x- and y-distances between grouped objects.

Discussion and Limitations

In this study, we explore performance in the entire 3D space. We deliberately opted to address various applications areas and maximize internal validity. Thus, we created a rather abstract task (i.e., selecting objects on the same screen level), used abstract content, and kept object parameters (e.g., color, size, and position) constant. We acknowledge that applying our findings to specific areas with different TCTs, like automotive UIs, would need further investigation in the future and is outside the scope of this study.

As our results show, the chosen task constitutes a complex visual search task that requires TCTs longer than 2 seconds. In fact, there are many real world applications to which this artificial task is not directly applicable. For example, the automotive domain requires tasks that are interruptible and do not need immediate responses for infotainment related applications. However, this abstract task allowed for precise measurements and gives us insights into the effect of spatial structuring along the z dimension.

Prior work found that perception of information works best behind the screen level. Hence, we decided to focus our study on this area of the screen. This is a limitation of the study and findings may not generalize to the area in front of the screen.

DEPTH LAYOUT TOOLS FOR PROTOTYPING S3D UIS

In the previous section we explored the core requirements for designing and prototyping S3D UIs. With the tools presented in this section, we aim to provide a means for designers to adhere to these requirements.

The third dimension makes it particularly challenging to use existing, state of the art, prototyping techniques for 2D user interfaces. As has been stressed earlier, paper prototyping has been shown to be highly useful in early stages of the development process [2] but is clearly limited when trying to arrange UI elements in 3D space. Hence, we built tools that can overcome the flat nature of paper for prototyping S3D layered UIs. The core idea is to augment paper prototyping in a way that maximizes the artistic freedom of the designer while providing implicit guidance towards usable products. In the following, we summarize the requirements and determine physical dimensions for tools that can support low fidelity prototyping in 3D space.

Viewing Distance and Depth Budget First of all, designers need to identify the distance between the viewer and the screen on which the UI is being presented. Usually this distance is defined by the context in which the UI is to be used. For example, in cars the usual distance between driver and dashboard is 75 cm. The viewing distance then determines the depth budget in which UI elements should be positioned to provide a comfortable viewing experience. Prior work showed this range to be 17.9 arc min to the front and 35.9 arc min to the back of the screen level [4].

Target Interface Dimensions The second requirement is the envisioned size of the target interface (width and height), for example a public display, a mobile phone, or a dashboard. Together with the viewing distance and depth budget it then allows for calculating width, height, and depth.

Number and Position of Depth Layers The depth layer positions and their number depend (a) on the distance of the viewer from the screen, which determines the available space (comfort zone) in z-direction and (b) of the minimum depth distance (3.6 arc min, see previous section).

Catering to these requirements allowed us to build prototyping tools that support the user in creating UIs, that (1) minimize the visual discomfort S3D can potentially cause and (2) allow different depth layers to be quickly and accurately distinguished. In this section, we describe two novel prototyping tools – the FrameBox and the MirrorBox. Both tools were designed to be used for arbitrary S3D UI design tasks and to map the specified requirements in the best possible manner.

FrameBox

The core idea behind the FrameBox is to allow users to work with a large variety of materials, including paper, films, and 3D mockups created with a laser printer, and to spatially position the different elements. Hence, we designed a cubic box made of acrylic glass with a number of slots that represent the different depth layers and allow for positioning UI elements on the z-axis in discrete steps. Within each slot, UI elements can be easily moved in the x-direction. Positioning on the y-axis can be achieved by means of paper-clips. In accordance to the specified requirements, we built a series of FrameBoxes for different application areas. One FrameBox was aimed for the design of automotive UIs and two for the design of mobile phones UIs (one for landscape and one for portrait mode).

The automotive FrameBox is based on the dimensions of a conventional freely programmable instrument cluster (12.3”) and a typical viewing distance of 750 mm. The viewing distance allows for positioning UI elements 44 mm to the front of the screen and 107 mm to the back of the screen to maintain the comfort zone. This results in the following dimensions of the FrameBox for an instrument cluster application: 293 x 110 x 151 mm (WxHxD).

For the mobile FrameBox we chose the size of the Samsung Galaxy S4 (5”) and a typical viewing distance of 350 mm. These values result in a comfort zone of up to 21 mm to the front and 50 mm to the back of the screen. Hence, the dimensions of the FrameBoxes are 111 x 62 x 71 mm.

All FrameBoxes were built using a laser cutter. The laser cutter templates are available for public use from our website[1]. As material we used transparent acrylic glass. A red line references the screen layer and makes positioning in front of or behind the screen easy for the designers (Figure 6).

MirrorBox

As a second prototyping tool, we designed the MirrorBox. We use a number of semi-transparent mirrors in the front and a surface-coated mirror in the back to allow users to see the mirrored image of a UI element projected from below (Figure 7). The mirrors are aligned one after another on top of a light source. Transparency films can be used to design UI elements, which are then sliced between the mirrors and the light source to make them visible to the user inside the MirrorBox.

[1] Templates: `http://www.hcilab.org/p/3Dprototyping`

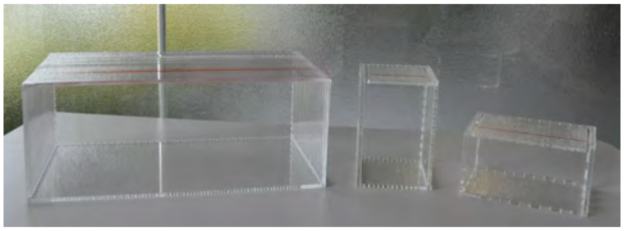


Figure 6: Frame Boxes for automotive and mobile phone applications (portrait and landscape).

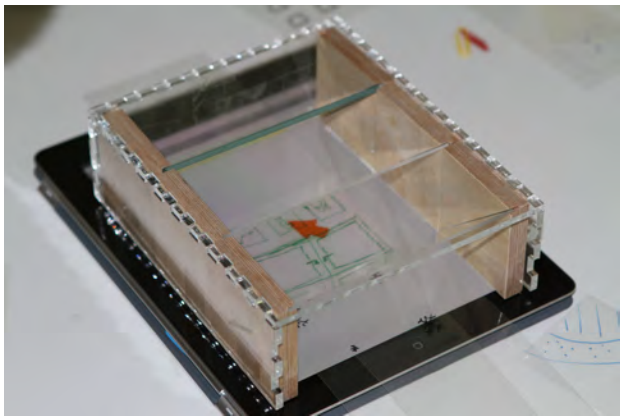


Figure 7: The MirrorBox with an iPad as a lighting source.

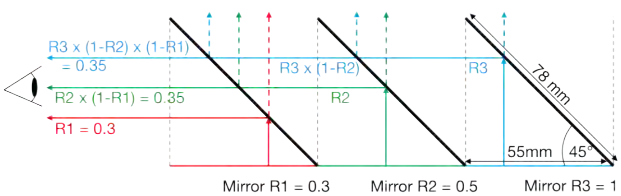


Figure 8: Principle of the Mirror Box: Mirror arrangements with reflectivity R1, R2, R3.

We constructed a multi-purpose MirrorBox consisting of 3 mirrors with a size of 125 x 78 mm. The mirrors are arranged behind one another and are horizontally tilted by 45 degrees. In this way, the mirrors generate three virtual layers by reflecting UI elements from below. We use a tablet as a lighting source. The mirrors have different reflectivity to provide the viewer with a similar brightness for all three virtual layers. The rear mirror reflects almost 100%, the mirror in the middle has a reflectivity of 50% and the foremost mirror has 30% reflectivity. This results in a total reflectivity of between 30% and 35% for each virtual layer (Figure 8). Since the mirrors are tilted by 45 degrees, the virtual images have a height of 55 mm. The distance between the layers is 55 mm. The outer dimensions of the MirrorBox are 125 x 55 x 165 mm.

EVALUATION

To evaluate the potential of our depth layout tools, we conducted two hands-on workshop sessions with experts in two fields, namely, automotive UIs and mobile phone UIs. We compared our approaches with paper prototyping, which is commonly used in early stages of development [2].

Procedure

As participants arrived, we first gave them a brief introduction on S3D UI design. We particularly focused on the guidelines explained earlier. The introduction took 10 minutes and slides were given to the participants as printouts for later reference. Then, the tasks for the hands-on phases were explained. We instructed the participants with a horizontal and a vertical prototyping task, depending on the workshop topic.

In the subsequent hands-on phase, participants were separated into two groups and asked to work on the tasks by means of three prototyping techniques. First, both teams used paper prototyping. As material we provided paper and post-its in different sizes and colors as well as colored pens. They were told that they had 15 minutes to work on the tasks and then had to present their ideas within no more than 3 minutes to the other group. After the presentation, one group was assigned the FrameBox and one group was assigned the MirrorBox and again given 15 minutes to work on the tasks. To each group, we also showed a brief concept video of the respective tool[2]. We told them that they can reuse and integrate their ideas and the ones of the other group. In addition to the paper prototyping material, we also provided them pieces of transparency films in different sizes and pens to write/draw on the film. After another 3 minute presentation, groups were asked to switch the depth layout tools and watch the other concept video. After 15 minutes we concluded the hands-on phase with another brief presentation. In total, each group created three prototypes, one with each prototyping tool (Figure 9).

Following the hands-on phases, participants were provided with a questionnaire that assessed their design skills, asked them to rank the tools, and to provide qualitative feedback. After that we entered a 30 minutes discussion phase led by two researchers. During the discussion phase, participants were asked to comment on strengths and weaknesses of the techniques, particular questions that came up during the hands-on phase, and observations made by the researchers.

Workshops

Design of S3D UIs is rapidly gaining importance in a lot of different areas. In two workshop sessions, we focused on automotive UIs and mobile phone UIs. The main reason for choosing these areas is that we envision 3D displays being commonly used in these contexts in the near future.

Automotive UIs are characterized by the fact that they draw the attention of the driver and, hence, direct the driver‘s sight off the road which must be critically minimized. This workshop session ran with nine members of the HCI department of BMW, grouped into two teams of four and five participants, respectively. All were experts in creating 2D UIs but nobody had designed a UI for a 3D display before. We refer to these participants as P1–P9 in the results section. The horizontal task for this session was to design a 3D dashboard for a car. In addition they were asked to integrate a conceptual navigation system within the dashboard that would provide guidance between two cities (vertical part).

[2]The concept videos are available from the ACM Digital Library and from `http://www.hcilab.org/p/3Dprototyping`.

Figure 9: Prototyping Workshop – After the two groups of participants received a brief introduction to S3D prototyping, they had to paper-prototype a 3D dashboard (1). After that groups used the MirrorBox (2) and the FrameBox (3) to refine their prototypes. After each session, groups presented their results (4) before filling in a questionnaire (5) and engaging into a discussion.

Mobile phones are ubiquitously used and the number of apps available is constantly growing. Many apps are used on the go and, thus, an easy to understand and use interface is important. This workshop session ran with six under- and postgraduates with backgrounds in either computer science or design, grouped in two teams with three participants each. All are experienced in developing applications for mobile devices. We refer to these participants as P10–P15 in the results section. The horizontal part of this session was to design the main screen of a mobile phone. For the vertical part, they had to design a widget that can be placed on the main screen.

Results

We collected results from the questionnaire and the discussion to get insights into how our concepts performed for creating low fidelity 3D prototypes. In addition, we report on observations made during the workshops.

A ranking of the three prototyping techniques shows that most participants favored the FrameBox (11 participants), followed by the MirrorBox (5) and paper prototyping (5). Further findings are grouped around four dimensions that we consider to be particularly important for prototyping tools, namely, expressiveness, usability, effort, and creativity. In the questionnaire, participants ranked the three prototyping techniques from one (best) to three (worst) to address these dimensions.

Expressiveness

Prototypes are often used to obtain early insights into concepts and, thus, the prototype needs to provide means for expressing and communicating the main idea. We explicitly asked participants whether they considered the prototype to have a high expressiveness. Answers show that participants attributed the highest expressiveness to the FrameBox ($Mdn = 1$), followed by MirrorBox ($Mdn = 2$), and paper prototyping ($Mdn = 3$). We performed a Friedman analysis of variance (ANOVA) that shows statistically significant differences between the three tools, $\chi^2(2) = 14.000, p = .001$. As follow up tests, we used three Wilcoxon tests for pairwise comparison with a Bonferroni correction applied. The Wilcoxon tests show statistically significant differences for FrameBox and paper prototyping, $Z = -3.226$, $p = .001$, as well as for MirrorBox and paper prototyping, $Z = -2.586$, $p = .010$. The differences between MirrorBox and FrameBox is not statistically significant, $Z = -1.355$, $p = .175$.

The discussions reflect these findings and provide further insights. Participants stated that "ideas are hard to communicate" (P4) using paper prototypes alone. Due to the two dimensional nature of paper "3D space is difficult to imagine" (P15), and it is "not sufficient for presenting the use of the z axis" (P5, P8, P9, P10, P13, P15). In contrast, FrameBox as well as MirrorBox represent the depth layers unambiguously and clarify depth positions. Participants feel the capabilities of the MirrorBox to be limited by just providing three layers, whereas "FrameBox offers a greater scope" (P7).

Usability

Prototyping in user-centered design is often done with users that are not prototyping experts. Thus, it is important that the tools are easy to use. We asked all participants whether they agree that the tools are easy to use. They rated paper prototyping best ($Mdn = 1$) followed by FrameBox ($Mdn = 2$) and MirrorBox ($Mdn = 3$). We performed a Friedman test (ANOVA) that shows statistically significant differences between the tools, $\chi^2(2) = 9.170, p = .010$. Using Bonferroni corrected Wilcoxon tests to follow up on this finding reveal statistically significant differences between the MirrorBox and FrameBox, $Z = -2.441$, $p = .015$, and between MirrorBox and paper prototyping, $Z = -2.565$, $p = .010$.

Participants believe the main reason for this to be that paper prototyping "is a well-known approach" (P10). Similarly, participants considered positioning elements on the layers to be very easy for the FrameBox (P2, P3, P8, P15). Creating depth layers as well as modifying their x, y, and z direction is perceived to be quick and easy. In contrast, positioning layers using MirrorBox is considered to be tricky since overlapping snippets impede each other. In addition, correctly positioning the transparency films (mirror-inverted) is considered to be confusing by some participants. Switching the depth position of layers is perceived as fast and easy.

Effort

Prototyping is particularly beneficial in iterative design processes. Hence, refined versions are frequently tested which suggests that the effort to create a prototype should be minimal. When asked how they rate the effort to create a prototype with each tool, participants rate paper prototype best ($Mdn = 1$), followed by the FrameBox ($Mdn = 2$) and the MirrorBox ($Mdn = 2$). The Friedman ANOVA shows no statistically significant differences, $\chi^2(2) = 2.393, p = .302$.

In the discussion, participants argued that paper prototyping is "good for first sketches and considerations" since it allows users to "generate and check out ideas quickly" (P9, P10, P14). Paper prototyping is considered to be effortless which "makes it easy to reject first sketches" (P10). The FrameBox supports less effortful design of realistic 3D impressions, whereas the MirrorBox is rated as more complex and sometimes even annoying, since the layers inside the small box are difficult to perceive without being positioned directly in front of it. Participants also felt that this makes collaboration among team members more difficult. This matches with our observations that the prototypes sparked quite a different amount of collaboration and discussion. With the MirrorBox, one member of the design team usually takes the task to position elements while the others draw the elements. For the FrameBox all participants design elements and position them themselves.

Creativity

Prototyping sessions are often performed in stages where design decisions are not made yet. Thus, the tool should not hamper the creativity of the user. Asked if the tools fully support the user's creativity, all three tools are rated equally good ($Mdn = 2$). A Friedman ANOVA shows, no statistically significant differences, $\chi^2(2) = 1.019, p = .601$.

The discussion showed that "paper prototyping fosters the flow of creativity due to starting from scratch on white paper" (P3, P12) and "offers the highest degree of freedom" (P13). Prototyping with paper and using the FrameBox fosters communication and collaboration. Participants feel inspired by the visual effect from the backlight and the mirrored layers of the MirrorBox. However, the mirror box somewhat "restricts the design space" (P4, P5, P8, P11, P12).

DISCUSSION

This paper provides (a) basic guidelines for designing user interfaces for 3D displays, that were gathered through a literature review and complemented by a laboratory study, and (b) prototyping tools supporting the design process for S3D UIs. We used the guidelines for the design of the presented tools and for instructing the participants during the workshops.

In the workshops, we were able to observe that the participants make use of the presented guidelines to fulfill their tasks. While the MirrorBox restricts the depth layout to only three depth layers, the FrameBox provides participants much more artistic freedom. Nevertheless, the participants stick to the guideline by using no more than six depth layers while prototyping with the FrameBox. Hence, this guideline can easily be followed by the users even if the tool does not explicitly implement this rule. For paper prototyping, we noticed that the participants have difficulties in observing the comfort zone as well as the minimal recommended distance between depth layers. Consequently, it is beneficial to integrate these guidelines in the tool in a way such that the designers can take the available depth relations into account. Furthermore, the participants propose an iterative process which involves a first concept draft based on paper prototyping and a later refinement using the FrameBox.

The conducted workshops show that our tools complement the strengths of paper prototyping – particularly low effort and support for creativity – with high usability and means for expressiveness. Our workshop participants try to cope with the fact that paper prototyping makes it difficult to position elements in 3D space. This comes at the cost of increased effort. For example, participants spend a considerable amount of time during the paper prototyping session making post-its 'stand' behind each other to reflect several layers or try to build 3D objects using paper. In contrast, the positioning of elements in 3D space is supported by MirrorBox and FrameBox. The use of our tools allows participants to concentrate on ideas, exploring the positioning of objects, adjusting fonts, and object size. The participants like to use paper prototyping in combination with the FrameBox as it has a low barrier for participation in the prototyping process but supports the spatial arrangement and the integration of 3D objects well. In contrast, the MirrorBox narrows the depth layout to three layers and does not allow the integration of 3D objects.

Furthermore, we have seen in the workshops that the prototyping tools help to effectively communicate design decisions within the team and to outside observers. The participants report that it is easier to understand the idea of the other group as they presented their results with the MirrorBox or FrameBox in contrast to seeing the results just as a paper prototype. This finding is supported by the results of the questionnaires regarding the expressiveness of the approaches. A low barrier for participation and the expressiveness is especially important for the UI development process as it often involves developers with different backgrounds.

Participants also express a clear interest in increasing the fidelity of the MirrorBox. While in our case, the iPad is only used as backlight, they suggest using an external monitor or tabletop surface that would allow users to sketch UI elements and display them immediately on the iPad.

Finally, we see potential in augmenting our tools with 3D elements, for example, from a 3D printer. In the automotive workshop we observed participants that exploit ways of modeling 3D objects. One group used the upper back part of the sticky notes to attach interface elements to paper. Another group used transparent scotch tape to create objects like mountains or buildings for the navigation system.

CONCLUSION

In this paper, we identify guidelines for creating UIs for 3D displays. Furthermore, we present MirrorBox and FrameBox, two display layout tools for prototyping S3D UIs. First, we provide an in-depth assessment of the requirements for building such user interfaces. Second, we report on how we designed the tools and evaluated them by means of two workshops with usability engineers. Third, we provide detailed information on how to adopt our idea to arbitrary UIs. Files to rebuild the tools are available from our website. In our evaluation, we show that our prototyping tools are, according to many aspects, superior to paper prototyping when it comes to designing for 3D displays as they increase creativity, usability, and expressiveness. For future work, we aim to apply the approach to high-fidelity prototyping.

ACKNOWLEDGEMENTS
We thank Carl Oechsner for his help during the user study. The research leading to these results has received funding from the European Union Seventh Framework Programme [FP7/2007-2013] under grant agreement no. 600851.

REFERENCES

1. Alper, B., Höllerer, T., Kuchera-Morin, J., and Forbes, A. Stereoscopic highlighting: 2d graph visualization on stereo displays. *IEEE Trans. Vis. Comput. Graph. 17*, 12 (2011), 2325–2333.
2. Baskinger, M. Cover story: Pencils before pixels: a primer in hand-generated sketching. *interactions 15*, 2 (Mar. 2008), 28–36.
3. Bowman, D. A., Kruijff, E., LaViola Jr, J. J., and Poupyrev, I. *3D user interfaces: theory and practice*. Addison-Wesley, 2004.
4. Broy, N., Alt, F., Schneegass, S., Henze, N., and Schmidt, A. Perceiving layered information on 3d displays using binocular disparity. In *Proc. PerDis 13*, 61–66.
5. Broy, N., André, E., and Schmidt, A. Is stereoscopic 3d a better choice for information representation in the car? In *Proc. AutoUI '12*, 93–100.
6. Häkkilä, J., Posti, M., Koskenranta, O., and Ventä-Olkkonen, L. Design and evaluation of mobile phonebook application with stereoscopic 3d user interface. In *CHI '13 EA*, 1389–1394.
7. Hick, W. E. On the rate of gain of information. *Quarterly Journal of Exp. Psych. 4*, 1 (1952), 11–26.
8. Huhtala, J., Karukka, M., Salmimaa, M., and Häkkilä, J. Evaluating depth illusion as method of adding emphasis in autostereoscopic mobile displays. In *Proc. MobileHCI '11*,
9. Julesz, B. *Foundations of cyclopean perception.* University of Chicago Press, 1971.
10. Lambooij, M., IJsselsteijn, W., and Fortuin, M. Visual discomfort and visual fatigue of stereoscopic displays: A review. *Journal of Img. Tech. and Sci. 53* (2009), 1–14.
11. Lee, J. C., Avrahami, D., Hudson, S. E., Forlizzi, J., Dietz, P. H., and Leigh, D. The calder toolkit: wired and wireless components for rapidly prototyping interactive devices. In *Proc. DIS '04*, 167–175.
12. Li, Y., Hong, J. I., and Landay, J. A. Topiary: a tool for prototyping location-enhanced applications. In *Proc. UIST '04*, 217–226.
13. Liu, L., and Khooshabeh, P. Paper or interactive?: a study of prototyping techniques for ubiquitous computing environments. In *CHI '03 EA*, 1030–1031.
14. Mahoney, N., Oikonomou, A., and Wilson, D. Stereoscopic 3d in video games: A review of current design practices and challenges. In *CGAMES* (2011).
15. McIntire, J. P., Havig, P. R., and Geiselman, E. E. What is 3d good for? a review of human performance on stereoscopic 3d displays. In *Proc. of Head- and Helmet-Mounted Displays XVII*, vol. 8383, SPIE (2012).
16. McWorther, S. W., Hodges, L. F., and Rodriguez, W. E. Comparison of 3-d display formats for cad applications. In *Stereoscop. Displ. and Apps II*, SPIE (1991).
17. Mikkola, M., Boev, A., and Gotchev, A. Relative importance of depth cues on portable autostereoscopic display. In *Proc. MoViD*, MoViD '10, ACM (New York, NY, USA, 2010).
18. Nakayama, K., and Silverman, G. H. Serial and parallel processing of visual feature conjunctions. *Nature 320*, 6059 (1986), 264–265.
19. Nojiri, Y., Yamanoue, H., Ide, S., Yano, S., and Okano, F. Parallax distribution and visual comfort on stereoscopic HDTV. In *Proc. IBC* (2006), 373–380.
20. Rogers, Y., Sharp, H., and Preece, J. *Interaction Design: Beyond Human-Computer Interaction*, 3 ed. John Wiley & Sons, New York, 2011.
21. Schild, J., Bölicke, L., LaViola Jr., J. J., and Masuch, M. Creating and analyzing stereoscopic 3d graphical user interfaces in digital games. In *Proc. CHI '13*,
22. Schneegass, S., Pfleging, B., Kern, D., and Schmidt, A. Support for modeling interaction with automotive user interfaces. In *Proc. AutoUI '11*, 71–78.
23. Snellen, H. *Probebuchstaben zur Bestimmung der Sehschaerfe*. Nabu Press, 2010.
24. Snyder, C. *Paper prototyping: The fast and easy way to design and refine user interfaces*. Morgan Kaufmann, 2003.
25. Stuerzlinger, W., and Wingrave, C. A. The value of constraints for 3d user interfaces. In *Virtual Realities*, Springer (2008), 203–223.
26. Sunnari, M., Arhippainen, L., Pakanen, M., and Hickey, S. Studying user experiences of autostereoscopic 3d menu on touch screen mobile device. In *Proc. OzCHI '12*, 558–561.
27. Treisman, A. M., and Gelade, G. A feature-integration theory of attention. *Cog. Psych. 12*, 1 (1980), 97–136.
28. van Beurden, M. H. P. H., Hoey, G. V., Hatzakis, H., and IJsselsteijn, W. A. Stereoscopic displays in medical domains: a review of perception and performance effects. In *Human Vision and Electronic Imaging*, vol. 7240, SPIE (2009).
29. Ventä-Olkkonen, L., Posti, M., and Häkkilä, J. How to use 3d in stereoscopic mobile user interfaces: Study on initial user perceptions. In *AcademicMindTrek '13*, ACM (New York, NY, USA, 2013), 39:39–39:42.
30. Weigel, M., Boring, S., Steimle, J., Marquardt, N., Greenberg, S., and Tang, A. Projectorkit: easing rapid prototyping of interactive applications for mobile projectors. In *Proc. MobileHCI '13*,
31. Yeh, Y.-Y., and Silverstein, L. D. Limits of fusion and depth judgment in stereoscopic color displays. *Human Factors: Journal of the Hum. Fac. and Erg. Soc. 32*, 1 (1990), 45–60.