T4 - Transparent and Translucent Tangibles on Tabletops

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ABSTRACT
In many cases, Tangible User Interfaces allow the manipulation of digital content with physical objects recognized by an interactive tabletop. Usually, such tangible objects are made of opaque wood or synthetic materials, thereby occluding the display. In this paper, we systematically investigate the promising potential of tangibles entirely made of transparent or translucent materials. Besides visualizing content directly below a manipulable tangible, transparent objects also facilitate direct touch interaction with the content below, dynamic illumination and glowing effects. We propose a comprehensive design space for transparent tangibles on tabletops based on a thorough review of existing work. By reporting on our own experiments and prototypes, we address several gaps in this design space, regarding aspects of both interaction and visualization. These include the illumination of tangibles as well as the precise input with transparent tangibles for which we also present the promising results of an initial user study. Finally, benefits and shortcomings of transparent tangibles are discussed and resulting design considerations are presented.

Author Keywords
Tangible User Interfaces; Transparent Tangibles; Interactive Surfaces.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION
In the last 15 years, various types of tangible user interfaces (TUI) for tabletop displays were created [8, 23]. They allow controlling digital content directly with tangibles on interactive surfaces. Thus, it becomes possible to blend haptic, physical real-world objects and the manipulation of virtual data. In particular, such TUIs take advantage of our natural motor skills by providing physical affordances (e.g., [23]).

Some of these systems already use (semi-) transparent objects to interact with virtual content. Surprisingly, few of them explicitly leverage the advantages of transparency and none of these have really investigated transparency in depth or systematically explored the design consequences it implies.

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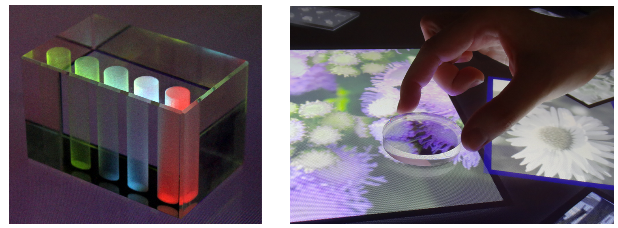

Figure 1. Engravings in a transparent tangible (left), Transparent token used to control image parameters (right)

Most TUIs use translucent materials only to be more aesthetically pleasing (e.g., [11, 12]). Furthermore, no general interaction and visualization principles specifically designed for transparent tangibles were proposed so far.

In this paper, we focus entirely on tangibles made of translucent and transparent materials, carefully inspecting this rich design space and surveying the existing literature. In our opinion, transparent or translucent tangibles on tabletops have a very promising potential for TUIs. Seeing visualizations through or even inside a physical object (Fig. 1, left) literally blends virtual data and its graspable representation. In that way, the physical object becomes less obtrusive, but manipulating digital artifacts can still be achieved in a tangible way (Fig. 1, right). Visualizing below the physical object instead of around the tangible also occupies less space on the display and offers possibilities for novel and more compact visual designs. Transparency of objects can be leveraged by interaction techniques such as flipping or stacking. Beyond that, digital content can be manipulated through the tangible by touch or pen input.

This paper has three main contributions and is structured as follows: (1) We present the results of a thorough review of existing research projects which realized TUIs with translucent tangibles on tabletops. In particular, we analyzed applied materials, existing form factors and types of applications, for which transparent tangibles were used so far. Based on this review, we propose a design space with aspects that were not yet considered by existing research.
(2) We report on our own investigations of transparent and translucent materials on interactive displays, aimed at closing promising gaps identified during our analysis. Among others, we tested several materials and experimented with illumination of laser engravings.
(3) With several prototypes and a study on the precision of transparent tangibles in comparison to both opaque tangibles and touch interaction, we show how the results of our investigations can be applied in novel use cases for transparent tangibles on tabletops.
(4) Derived from the results of our own experiments, we sum-

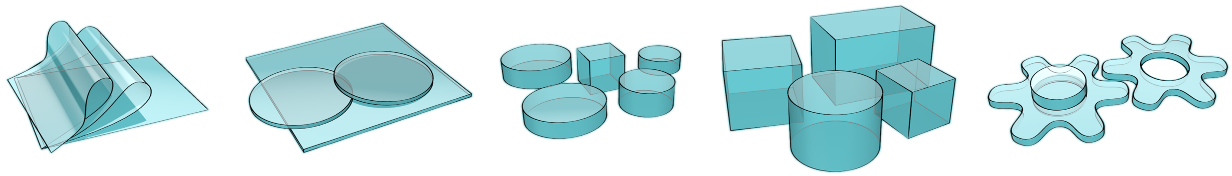

Figure 2. a) Foils [9, 13, 15] b) Plates [9, 21, 25, 28] c) Tokens [4, 6, 7, 9, 11, 12, 17, 19, 22] d) Blocks [1, 25, 30] e) Compound Forms [10, 29] Categorization of form factors for transparent and translucent tangibles and their usage in related work

marize advantages and limitations of transparent tangibles and present resulting design considerations for both interaction and visualization.

THE T4 DESIGN SPACE

As a starting point, we conducted a thorough review of existing research in translucent and transparent tangibles. The goal of our analysis was to identify aspects of the T4 design space which were not yet considered and fully investigated. Whereas we cannot guarantee completeness, we were specifically looking for the usage of transparency and tried to be as comprehensive as possible. To our knowledge, no such analysis on the design space of transparent tangibles has been done before. Our analysis is limited to tangible user interfaces on tabletops, a relevant category of TUIs [26]. TUIs not involving interactive surfaces were not in the focus of our review.

In the following, we will present our analysis according to five different design dimensions: (1) form factors of translucent tangibles, (2) materials transparent and translucent tangibles can be made out of, (3) roles, functionality and purposes of transparent tangibles, as well as (4) visualization and (5) interaction techniques. Moreover, we analyzed for which kinds of applications such tangibles were used.

Form Factors

Form and size are responsible for a tangible's visual appearance and interaction capabilities. Thus, as a first step, we thoroughly analyzed the form factors of transparent and translucent tangibles and classified them into basic forms (foils, plates, tokens and blocks) and compound forms. An overview is provided in Fig. 2. In the following, we explain the characteristics of each form factor and provide examples of how they were applied in existing systems.

Foils (Fig. 2a) are very thin and made of bendable material. In comparison to other form factors they are however less graspable. On the other hand, they allow a more or less direct touch interaction with content below, due to their low thickness, which also creates the opportunity for stacking. Especially in the sense of toolglasses and magic lenses as proposed by Bier et al. [3] transparent foils are useful. Systems using foils in that form are interfaces such as geo-lenses or graphic filters [9, 13, 15]. There they represent an additional layer or a different view on the data presented underneath. Due to the transparency of the foil, changes of the content underneath can be easily perceived by the user.

Plates (Fig. 2b) are of similar size as foils. They are slightly thicker and not bendable, but thus more graspable and easy to pick up or move around. However, plates are still thin enough to give users the impression of directly touching the content underneath. Rectangular transparent plates were applied for instance by systems such as DataTiles [21] and Tangible Tiles [28]. They use plates as data containers, as portals to physical devices or for invoking functions such as magnification. Our review of existing literature revealed that other shapes than rectangular ones were hardly applied up to now. An exception is the passive lens of MetaDesk by Ulmer and Ishii [25] which consists of a round flat transparent plate with wooden frame.

Tokens (Fig. 2c) are smaller in size than foils and plates, but thicker. Touch input on tokens is different from previous forms since a parallax effect occurs due to the thickness. As a result, the interaction with the content below is less direct. Instead, tokens rather offer the affordance of handles or user interface controls, because of their graspable form and size. They lend themselves for precision grips, allowing fine adjustments [16, 23]. Our literature review revealed that completely transparent tokens were hardly used so far. One exception is the NUIverse application [19]. It applies transparent tokens to invoke menus and to show the current menu level below it. Some systems such as the reacTable [12], Capstones [4], Ficons [7], Transparent Haptic Lens [6], or FacetStream [11] apply transparent tokens as well. However, they are tracked by opaque visual markers or made out of fiber optics which partially occlude the content below and thus require it to be displayed outside of the token. Accordingly, they do not explicitly leverage transparency and are mainly used to make applications visually more appealing. Translucent back projection has been used to illuminate tokens from below by Izadi et al. [9].

Blocks (Fig. 2d) are bigger and thicker objects such as cubes or cylinders. Due to its size, a block has less the affordance of a movable handle but rather that of a fixed positioned object. In particular, bigger blocks are better suited to be grasped with power grips and less for precision grips [23]. Translucent blocks were used for example by the MetaDesk system [25]. They represented buildings on a virtual map and were made of translucent material to be less obtrusive. Another example is TZee [30]. It allows manipulating 3D objects using touch gestures on the surface of a transparent block. Lumino [1] uses fiber optics to show content on top of their blocks.

Compound forms (Fig. 2e) are combinations of the mentioned basic shapes. Examples for such combinations are some of the SLAP Widgets [29] or the remote controllers by Jansen et al. [10]. For instance, these systems realized sliders and turning knobs made of transparent acrylic. This can be seen as combinations of tokens and plates.

Materials

As a next step of our analysis, we investigated which materials were used so far to produce transparent tangibles of the mentioned form factors. In most systems, translucent tangibles are made of acrylic glass. Examples for that are the plates of DataTiles [21] and TangibleTiles [28]. Furthermore, the stacked blocks of the TZee input device [30] are made of acrylic material. The SLAP Widgets [29] and the tangible remote controllers by Jansen et al. [10] also uses acrylic glass for some tangibles and silicone for others.

Foils are usually made of very thin and bendable transparencies (e.g., cellulose acetate) [13, 15]. The TaPS widget [17] combines foil and acrylic glass. A scattering foil is attached to the top side of the transparent object and scatters light depending on the viewing angle. This allows specific users seeing content below the tangible, whereas from a different viewing angle the visualization is blurred.

Further options are silicone, polyethylene or similar translucent elastic materials. For example, elastic material is applied for the keyboard and keypads of the SLAP widgets [29]. The Photoelastic Touch system [22] also uses elastic material, amongst others, for realizing a paint application. Additionally, there is the option to apply fiber optics. This material was used to realize stacking of tangibles [1] and to transmit content from the display to the side or another part of the tangible [31]. Fukuchi et al. [7] applied glass fibers to transmit light from the display to the top side of their Ficon tangibles. In this way, the tangible objects are not perceived as completely transparent, but the content underneath becomes visible at a higher position.

Role and Function of Translucent Tangibles

In addition to analyzing the form factors of transparent tangibles and hardware aspects, we investigated for which general purposes translucent tangibles were used so far. We found that they can be divided into four categories: Tangibles for invoking functions, tangibles as physical controls, tangibles as representatives and tangibles as data containers. In the following we will discuss these categories in more depth, considering how transparency was leveraged.

Tangibles for invoking functions: Many transparent or translucent tangibles are used for invoking functions that affect the digital content visualized below the object, e.g. providing different views or manipulation of the presented information. Examples for that are tangible magic lenses [13, 15, 26], the function tiles of the Tangible Tiles system [28] or the application tiles of DataTiles [21]. By putting the tangible on an interactive surface or by positioning it on a digital object, specific functions, such as magnifying the content below, translating text or invoking an application are automatically applied. This allows a more direct interaction, since the function has a physical representation and is invoked directly on the target object. Furthermore, the transparent tangible is unobtrusive and does not obscure the digital content below. For these kinds of tangibles mainly foils and plates were used. Their size is big enough for covering a quite large area of the display where the respective function is applied. Beyond that, they are thin enough to provide an undisturbed view to the digital artifacts below.

Physical Controls: In some application scenarios transparent tangibles are used as dedicated physical controls. They allow manipulation of digital content by interactively changing parameters. The SLAP Widgets [29] and the remote controllers of Jansen et al. [10] are two prominent examples for this. Virtual user controls are represented by graspable counterparts offering physical affordances and tactile feedback. These systems leverage transparency by showing scales and labels below the tangibles and changing these visualizations dynamically. Similar to this are the graspable menu of NUIverse [19], the parameter tiles of DataTiles [21] or the PIN entry widget of TaPS [17].

Changing parameters is usually achieved by positioning [29] or rotating token-sized tangibles [11]. Some systems further guide these manipulations by considering physical constraints e.g., by moving one object along the other [10, 29] or by restricting pen movements with engravings [21]. Several systems also realize direct touch interaction on the surface of tangibles such as plates or blocks [17, 29, 30]. The mentioned tangibles are applied in a decoupled way from content that they are affecting, typically not being placed directly on the digital object, but further away.

Representatives: Often, transparent tangibles are applied to represent particular digital content, e.g. a specific entity or element of a visualization. Examples for that are the Phicons of MetaDesk [25]. Furthermore, the TaPS widget [17] was used to represent a playing card and some tiles of the Data Tiles system represent connections to physical devices or places [21]. The associated digital content is visualized below the transparent object [17, 21] or the shape of the tangible communicates which content it represents [7, 22, 25]. For representatives mainly tokens and blocks are applied.

Data Containers: Transparent tangibles were also used as data containers. In contrast to representatives they are not constantly associated with one item, but allow dynamically changing this association. Transparent plates can be associated with a digital object by placing the tangible on top of it [28] or by performing a pen stroke from one plate to the other [21]. Thereby, the digital objects are visualized below the plate which serves as a container. As a result, the associated content can be moved or carried around with its container.

Visualization and Digital Feedback

In TUIs with opaque tangibles the associated content is usually shown on the display area around (Fig. 3a) the tangible. This results in the taking up of space and leads to restrictions in the design of the visualization. The most obvious potential of transparent tangibles is the possibility to visualize digital content also below (Fig. 3b) physical objects. The results of our review revealed that this was leveraged by most of the existing research projects in this field [10, 13, 17, 21, 28, 29].

However, we are confident that glass and other translucent materials have more characteristics which are promising for TUIs. One possibility is taking advantage of internal light refractions. This can be used to realize illumination effects

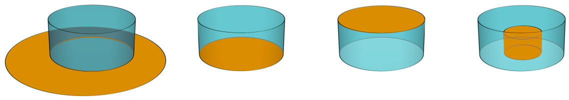

Figure 3. Visualization of digital content (from left to right): a) around; b) below; c) on top; d) within

on the top side (Fig. 3c and 4c) of a tangible by transmitting light from the display to the upper surface of the object [7]. Of course, such an effect can also be achieved by projecting visualizations from above onto an opaque object [24, 20]. However, for top projections more hardware and calibration is necessary. Furthermore, it may lead to problems during interaction, since hands and fingers cast shadows.

One problem of visualizing digital content below a transparent object is the restricted space given by the size and shape of the tangible. This especially affects tangibles used as data containers. So far, no general interaction and visualization principles were created to deal with this problem.

Furthermore, transparent objects bear the potential of visualizing content within (Fig. 3d) their bodies. To our knowledge, this was not yet considered for tangibles on interactive displays. One possibility to realize internal visualizations is applying passive optical scatterers [31], whereby small air pockets in solid material are illuminated by LEDs.

Interaction

We found that interacting with transparent tangibles is usually done in the same way as with opaque ones. In current systems, one main way of interacting with translucent tangibles is by their position or movement. This includes *translation, rotation and orientation,* and *placing them at specific positions or onto a target object*. Such target objects are usually quite large and the placement is coarse. Although the transparency of tangible objects facilitates precise positioning on small visual targets, this aspect was not yet considered by existing systems.

Beyond moving tangibles across the display, other interaction techniques, such as *tilting* (for releasing content) and *flipping* (for negating functions) were applied [28]. When using flipping, multiple functions could be mapped to one object by attaching individual markers to different sides of a tangible while still visualizing content below due to the transparency.

Furthermore, *stacking* has been proposed for thin objects such as foils for realizing a combination of associated functions [13, 15]. Stacking for larger form factors however was not investigated much and existing stacking techniques (e.g., [1, 4, 14]) rarely make use of transparency, although such tangibles could allow see through visualization or even interaction through several levels. Chan et al. [4] used capacitive tangibles to track stacking, but the necessary connectors and internal wiring severely reduced the transparency. Voelker et al. [27] demonstrated how capacitive tangibles can be made transparent using indium tin oxide foils, potentially leveraging this limitation in the future. As an alternative to actual stacking Ebert et al. [5] presented non-transparent tangible rings that are of different diameters and can be placed into each other, thereby representing a combination of information layers. Additionally to the grouping of tangibles the ring form of these tangibles allows touch within the lens-like area as the user can see the content of the lens underneath, similar to actual transparent tangibles.

As mentioned before, one field of application for transparent tangibles is to use them as data containers. However, in existing systems [28] such containers usually hold only one object not several ones. How to interact (e.g., by touch or pen input) with several items through a transparent plate and which visualization techniques can be applied for such cases was not yet much focused on by existing research.

ENRICHING THE DESIGN SPACE

Based on the under-explored areas of the T4 design space, which we identified in our literature analysis, we started experimenting with different translucent materials. In particular, we used low-cost materials, such as glass and acrylic glass in different form factors, and created passive tangibles without any electronic augmentation. Besides form factors such as plates or tokens, we also focused on translucent blocks (e.g., cubes, pyramids or cylinders), since they were hardly used so far for TUIs.

Our tests were mainly done on a Samsung SUR40 tabletop. To create unobtrusive tangibles, we created transparent tags from IR-reflecting foil. These tags are hardly perceivable by the human eye, especially when illuminated by the display.

Beyond that, we had a deeper look at interaction techniques which are specifically relevant for transparent tangibles. We realized several example applications which explicitly make use of transparent and translucent tangibles, showcasing the benefits of T4 in several novel ways. Specifically, we concentrated on precise positioning of transparent tangibles, which we also evaluated in a small user study.

Illumination of Translucent Materials

In the following we will present the results of our experiments concerning illuminating translucent materials with light from the tabletop and the prototype of a notifier tangible based on these findings.

Plexiglas EndLighten and Back Projection Foil: As a transparent object is put on the tabletop, we illuminate it from below (e.g., we show a square when a cube is placed on the display and a circle for a cylinder).

In this way, we tested Plexiglas EndLighten and objects made of common glass. EndLighten is a translucent acrylic material infused with colorless light diffusing particles. When such an object is illuminated with colored light the color becomes visible throughout the whole body of the object, especially along the edges (e.g., the top side of a cylinder or cube). In this way, an illumination effect can be produced which is clearly visible in daylight (Fig. 4a).

Illuminating a transparent glass object from below does not have the same effect. Due to total reflection, the content visualized below the object is visible only when looked at from above. However, an illumination effect can be achieved by

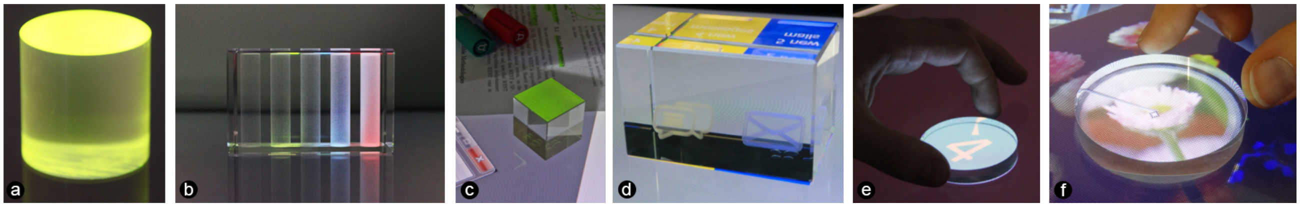

Figure 4. From left to right: (a) EndLighten, (b) different density laser engravings, (c) ambient notifier using backprojection foil, (d) ambient notifier using laser engravings, (e) generic dial knob control, (f) dial knob for image manipulation.

attaching back-projection foil on top of a fully transparent glass object. As a result, the illumination effect is visible on the parts where the foil is located. This way, it is possible to produce transparent unobtrusive tangibles which can change their color dynamically on their top side, lifting the illumination from the tabletop (Fig. 4c).

Laser Engravings: We thoroughly investigated illumination of laser engravings. A 3D model is engraved with a laser inside a transparent glass object. This technique is also known as Laser Induced Damage (LID) (see [18]). When illuminated from below (e.g., by an LED [31]), the engraved shape (or parts of it) reflects the light and starts glowing. Other parts of the object are not affected by the illumination.

However, since light emitted from an LCD display is less intense than light from an LED, the glowing effect is also less visible. Three main parameters influence the visibility of the engraving: general size of the illuminated engraving, density of the engraved points, and the distance of the individual point from the display. In our experiments we tested different positions of engravings within a block, including engravings closer to the table display and tilted engravings, as well as different densities (Fig. 4b). Our tests show that a balance between the visibility of the effect when illuminated and the transparency needs to be achieved, with high densities scattering too much light while low densities are barely visible.

We also found that engraved objects with a tilted angle work best as this enlarges the size of the area that is reached directly by the illumination from the tabletop below and the strength of the illumination effect.

Use Case - Ambient Notifier: Using our findings on the illumination of transparent tangibles, we implemented both a small notifier with back-projection foil and a larger notifier with engraved icons which are illuminated when new messages or mails are received (Fig. 4c+d). We imagine an office scenario with a multitouch desktop (like in [2]), where physical and virtual documents are mixed and used in parallel. Here lifting the visualization up into the third dimension could help make the notification visible even in cluttered workspaces.

Interaction with Transparent Tangibles

We extend the possible interaction vocabulary of transparent tangibles on a tabletop by proposing precise positioning of tangibles in addition to stacking of transparent plates, flipping, and touch input through transparent tangibles.

Touch-Input: Transparent tangibles are suitable for touch interaction, as visualizations can be directly underneath the tangible, allowing both content and controls to be shown below. As foils and plates are rather thin form factors it is possible to detect touch through them. This allows users to "directly" touch elements presented underneath, e.g. for selection of specific data elements that are within a container tangible. Tokens and blocks do not lend themselves for precise touch due to their thickness and resulting parallax effects. It is also harder to track exact input because of refractions and diffusion of light within the tangible. While other hardware setups allow these touch recognitions (e.g., [30]), we propose coarse, full-tangible touch input, covering the whole upper side of the tangible. This reflects light to the bottom where it is recognized as an unusually large blob. This way it is possible to recognize a users tapping on the tangible with his or her flat hand.

Use Case - Dial Knobs for Image Manipulation: Making use of the transparency for both showing content underneath and detecting touch on top of transparent tangibles, we propose round tokens similar to physical dial knobs. They can be used for changing property values (Fig. 4e) using the space below the tangible for presentation of the actual values and are hence occupying less space within the application context. We implemented an image manipulation application where such tokens can be used to adjust image parameters, such as brightness or contrast. The live results of the changed values are shown below the tangible in form of a magic lens (Fig. 4f) and only on confirmation by the user through touch on the tangible, the change will be propagated to the whole image.

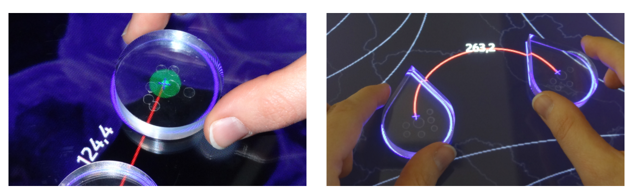

Figure 5. Measurement tool for straight lines (left) and curves (right), as used in our study.

Precise Positioning: As with existing opaque tangibles, it is possible to reposition translucent objects by moving them across the interactive surface. However, we suggest that transparency allows for more precise positioning. Especially with form factors such as foils, plates and tokens, small virtual objects below can be targeted in a precise way which is hard to achieve with opaque tangibles. To further ease precise positioning, visualizations such as crosshairs representing the center of the tangible can be shown.

Use Case - Measurement Tool: We created a measurement tool that uses the possibility of precise positioning and context awareness of transparent tangibles (Fig. 5). When the user places two tangibles on the tabletop, their position and rotation define the four control points of a cubic bezier curve drawn between the two tangibles on top of a background image. The current arc length is displayed between the tangibles at all times. When the tangibles are roughly facing each other, the curve snaps to a straight line instead, allowing the user to measure both distances between points as well as the length of a wide range of curves in the underlying image.

Due to the transparency, the background is barely occluded, providing a clear view on the image while still benefiting from the affordances of physical, graspable tokens. Other test applications we implemented, not shown here, include transparent tangible graph lenses and tangibles for color mixing.

EVALUATION OF PRECISE POSITIONING

We believe precise positioning to be one of the main advantages of transparent tangibles. Therefore, we did a small quantitative user study to evaluate our measuring tool prototype and compare how precise and fast transparent tangibles can be positioned compared to both opaque tangibles and normal touch interaction.

Goals and Method

Twelve unpaid participants, students and colleagues from our department, took part in the study (10 male, 2 female). Their age ranged from 24 to 53 (M = 32.4, SD = 10.3). All tests were done on a Samsung SUR40 40" tabletop with PixelSense technology. We tested three input modalities (touch, transparent tangibles and opaque tangibles) in a within-subjects design in two different tasks. The dependent variables were completion time and precision. The order of the tasks and the order of the modalities in each task was counterbalanced to avoid learning effects. For each modality and task, ten runs were done, the first being used for training purposes and not recorded.

In task $T1$, for each run, two positions were clearly highlighted on a background image. The participants were asked to position an object (tangible or virtual object) on each position as fast and accurately as possible and then confirm by pressing a button in the corner of the display (Fig. 5, left). In task $T2$, instead of points, a segment of a cubic bezier curve was shown and the participants were asked to use two control objects to recreate the curve, overlaying it as accurately and fast as possible. In this task, the control objects' positions defined the start and end point of the curve and their rotations defined the respective control points (Fig. 5, right).

For the transparent tangibles, the pivot point was shown underneath, while for the opaque tangibles it was shifted to the border of the object, to minimize occlusion by the tangible itself. For the touch condition, the control objects were virtual and could be dragged and rotated by touch.

Before each task block the task was explained to the user. After completion of a task block, a short questionnaire similar to the NASA TLX was filled out by the participants.

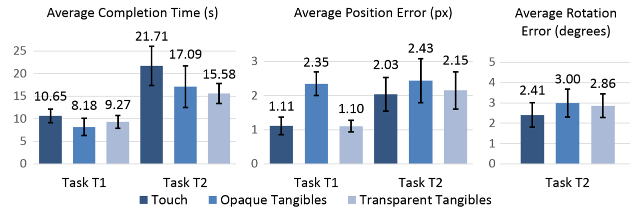

Figure 6. Overview of our study's results for the points task (T1) and the curves task (T2). Values given are the means, the error bars show the 95% confidence intervals.

Results

Of the 324 samples per task two outliers clearly attributable to measuring errors were removed and average results for each test computed. Precision for T1 was defined as the average pixel distance between the centers of the target and the tangible/virtual control object. For T2 both this positional precision and the average rotation error of the control objects was examined. Completion time and precision for task T1 and rotation error for T2 were examined with repeated measures ANOVAs with Greenhouse-Geisser correction. Completion time and position error for T2 were tested with Friedman's ANOVA instead, after Shapiro-Wilk tests indicated that the assumption of normality was violated.

For completion time in T1 we determined significant differences between the input modalities ($F(1.27, 14.01) = 9.30, p = .006$ for T1 and $\chi^2(2) = 12.666, p = .001$ for T2). For T1, post hoc tests with Bonferroni correction revealed that touch input was significantly slower than both opaque ($p = .015$") and transparent tangibles ($p = .002$) but didn't show a significant difference between opaque and transparent tangibles ($p = .333$). For T2, Wilcoxon tests with Bonferroni correction were applied, again indicating that users were faster with both opaque tangibles ($Z = -2.746, p = .003$) and transparent tangibles ($Z = -3.059, p < .001$) compared to touch. No significant difference between opaque and transparent tangibles was found ($Z = -0.549, p = .622$).

There was a significant effect of the input modality on the precision in T1, $F(1.33, 14.66) = 57.92, p < .001$. The Bonferroni corrected post hoc tests showed no significant difference between touch and transparent tangibles ($p > .999$) while both were significantly more precise than opaque tangibles ($p < .001$ for both). The results for the precision in T2 were not significant with $\chi^2(2) = 3.500, p = .191$ for the position error and $F(1.934, 21.276) = 2.082, p = .150$ for the rotation error.

We believe that the inconclusive results for T2 are partly caused by a lack of precision in the detection of the marker rotation by the Samsung SUR40 (up to approx. 1–2°). Also, we think that users concentrated more on the overall quality of fit of the curves than the position of the two end points that were actually measured. Still, the results, especially for T1, indicate that transparent tangibles allow for more precise positioning compared to opaque tangibles while not sacrificing the efficiency of physical controls (Fig. 6). This is also supported by the questionnaires: Although we cannot report on them in detail due to the lack of space, the average perceived speed and precision were best for transparent tangibles in both tasks. For example, perceived precision (on a scale of 1 - very good, to 5 - very bad) was 1.58 for transparent tangibles, compared to 1.92 and 2.25 for opaque tangibles and touch in T1.

DISCUSSION OF DESIGN CONSIDERATIONS

Building on the analysis of related work, the proposed design space and our own experiments, we identified benefits and possible drawbacks of translucent tangibles that we describe in the following. We discuss these aspects of transparent and translucent tangibles for other user interface designers to consider.

Advantages of Translucent Tangibles: A number of advantages directly follow from transparency itself: Transparency facilitates precise positioning of tangibles on the underlying content as has been shown in our quantitative study. Also, content can be shown underneath the tangibles, allowing for better utilization of screen space as well as enabling even generic tangibles to be used for different, specific uses.

Depending on the form factor, transparency in tangibles enables direct touch of objects underneath, as presented in our image manipulation application, and it also makes stacking of thin tangibles feasible. Finally, interesting and useful lighting effects can be employed to signal information and lift content from the surface into the third dimension.

Usefulness of Different Form Factors: Depending on the application, an appropriate form factor should be used. Blocks are best suited as information representatives and communicate their function through their form and, possibly, engravings. Tokens, plates and foils should be used for more dynamic interaction. Especially tokens are easily graspable allowing fine grained manipulation and widget-like functionality. Transparent plates and foils allow even more direct manipulation of the underlying content.

It should however be noted that technical aspects limit the applicability of interaction techniques for different form factors. For example, as mentioned earlier, precise touch interaction is generally not feasible on tokens that are too thick. On the other hand, smaller tokens, plates, and especially thin foils are less graspable, making careful design considerations necessary.

Assigning and Displaying Functionality: There are several possibilities for binding functionality to a tangible: First, a function can be fixed to one particular tangible. Alternatively, functions can be bound through a menu, either by stamping with the tangible, assigning by touch from a menu displayed on the tabletop, or by choosing from a menu directly below the tangible. Finally, "copying" functionality from other tangibles (e.g., by putting them on top of each other) is also possible in an elegant way using transparency.

Without the illumination of the tabletop the transparent tangibles do not convey complex visual information. Different approaches are reasonable that can be loosely categorized: Using different shapes and engravings are static methods. The same holds true for color tinting of the tangibles translucent material. On the other hand, the currently assigned function can dynamically be displayed underneath, inside, or on top of the tangible, making use of the same properties: shape, symbols or text, and color.

While being able to show content underneath is one important advantage of transparent tangibles, the size of the tangible objects is fixed and unchangeable, as in most TUIs. Hence, the representation of the content visualized below might have to be adapted to its size.

CONCLUSION

In this paper, we carefully explored the promising design space of transparent and translucent tangibles for tabletop interaction. In particular, we analyzed how transparent tangibles were used in previous systems and proposed a design space including dimensions like material, form factor, visualization opportunities, functional role, and interaction techniques.

To advance the current state of the art, we proposed several solutions to close some promising gaps in the design space. This includes illumination of translucent materials on top and within the tangible using laser engravings. As a result of our experiments we presented use cases which explicitly make use of transparent materials for TUIs to illustrate their potential. We also summarized the possible interaction vocabulary for transparent tangibles and contributed a study on precise positioning of graspable objects directly on digital surface content. The ability of transparent tangibles to show virtual content directly below makes them very space-efficient and also allows for a flexible assignment of functions. Furthermore, direct touch input is facilitated with transparent foils and plates, and stacking of objects becomes possible.

We hope the community will pick up some of the proposed ideas, further advance the design space and include them into their projects. For future work we will extend our application cases and focus more on real world applications and upcoming desktop setups like [2]. Furthermore, we plan to investigate better marker arrangements for easier stacking and compound transparent tangibles.

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REFERENCES

1. Baudisch, P., Becker, T., and Rudeck, F. Lumino: Tangible blocks for tabletop computers based on glass fiber bundles. In *Proc. of CHI '10*, ACM (2010), 1165–1174.

2. Bi, X., Grossman, T., Matejka, J., and Fitzmaurice, G. Magic desk: Bringing multi-touch surfaces into desktop work. In *Proc. of CHI '11*, ACM (2011), 2511–2520.

3. Bier, E. A., Stone, M. C., Pier, K., Buxton, W., and DeRose, T. D. Toolglass and magic lenses: The see-through interface. In *Proc. of SIGGRAPH '93*, ACM (1993), 73–80.

4. Chan, L., Müller, S., Roudaut, A., and Baudisch, P. Capstones and zebrawidgets: Sensing stacks of building blocks, dials and sliders on capacitive touch screens. In *Proc. of CHI '12*, ACM (2012), 2189–2192.
5. Ebert, A., Weber, C., Cernea, D., and Petsch, S. Tangiblerings: Nestable circular tangibles. In *CHI '13 Extended Abstracts*, ACM (2013), 1617–1622.
6. Follmer, S., Leithinger, D., Olwal, A., Cheng, N., and Ishii, H. Jamming user interfaces: Programmable particle stiffness and sensing for malleable and shape-changing devices. In *Proc. of UIST '12*, ACM (2012), 519–528.
7. Fukuchi, K., Nakabayashi, R., Sato, T., and Takada, Y. Ficon: A tangible display device for tabletop system using optical fiber. In *Proc. of ITS '11*, ACM (2011), 1–1.
8. Ishii, H. Tangible bits: Beyond pixels. In *Proc. of TEI '08*, ACM (2008), xv–xxv.
9. Izadi, S., Hodges, S., Taylor, S., Rosenfeld, D., Villar, N., Butler, A., and Westhues, J. Going beyond the display: A surface technology with an electronically switchable diffuser. In *Proc. of UIST '08*, ACM (2008), 269–278.
10. Jansen, Y., Dragicevic, P., and Fekete, J.-D. Tangible remote controllers for wall-size displays. In *Proc. of CHI '12*, ACM (2012), 2865–2874.
11. Jetter, H.-C., Gerken, J., Zöllner, M., Reiterer, H., and Milic-Frayling, N. Materializing the query with facet-streams: A hybrid surface for collaborative search on tabletops. In *Proc. of CHI '11*, ACM (2011), 3013–3022.
12. Jordà, S., Geiger, G., Alonso, M., and Kaltenbrunner, M. The reactable: Exploring the synergy between live music performance and tabletop tangible interfaces. In *Proc. of TEI '07*, ACM (2007), 139–146.
13. Kim, K., and Elmqvist, N. Embodied lenses for collaborative visual queries on tabletop displays. *Information Visualization 11*, 4 (2012), 319–338.
14. Klum, S., Isenberg, P., Langner, R., Fekete, J.-D., and Dachselt, R. Stackables: Combining tangibles for faceted browsing. In *Proc. of AVI '12*, ACM (2012), 241–248.
15. Koike, H., Nishikawa, W., and Fukuchi, K. Transparent 2-d markers on an lcd tabletop system. In *Proc. of CHI '09*, ACM (2009), 163–172.
16. MacKenzie, C., and Iberall, T. *The Grasping Hand*. Advances in Psychology. Elsevier Science, 1994.
17. Möllers, M., and Borchers, J. Taps widgets: Interacting with tangible private spaces. In *Proc. of ITS '11*, ACM (2011), 75–78.
18. Nayar, S. K., and Anand, V. N. 3d volumetric display using passive optical scatterers. In *ACM SIGGRAPH 2006 Sketches*, SIGGRAPH '06, ACM (2006).
19. NUIverse. A natural user interface to explore the universe, http://nuiverse.com/.
20. Patten, J., Ishii, H., Hines, J., and Pangaro, G. Sensetable: A wireless object tracking platform for tangible user interfaces. In *Proc. of CHI '01*, ACM (2001), 253–260.
21. Rekimoto, J., Ullmer, B., and Oba, H. Datatiles: A modular platform for mixed physical and graphical interactions. In *Proc. of CHI '01*, ACM (2001), 269–276.
22. Sato, T., Mamiya, H., Koike, H., and Fukuchi, K. Photoelastictouch: Transparent rubbery tangible interface using an lcd and photoelasticity. In *Proc. of UIST '09*, ACM (2009), 43–50.
23. Shaer, O., and Hornecker, E. Tangible user interfaces: Past, present, and future directions. *Foundations and Trends in Hum.-Comput. Interact. 3*, 1-2 (Jan. 2010), 1–137.
24. Spindler, M., Cheung, V., and Dachselt, R. Dynamic tangible user interface palettes. In *Proc. of INTERACT '13* (9 2013), 159–176.
25. Ullmer, B., and Ishii, H. The metadesk: Models and prototypes for tangible user interfaces. In *Proc. of UIST '97*, ACM (1997), 223–232.
26. Ullmer, B., Ishii, H., and Jacob, R. J. K. Token+constraint systems for tangible interaction with digital information. *ACM Trans. Comput.-Hum. Interact. 12*, 1 (Mar. 2005), 81–118.
27. Voelker, S., Nakajima, K., Thoresen, C., Itoh, Y., Øvergård, K. I., and Borchers, J. Pucs: Detecting transparent, passive untouched capacitive widgets on unmodified multi-touch displays. In *Proc. of ITS '13*, ACM (2013), 101–104.
28. Waldner, M., Hauber, J., Zauner, J., Haller, M., and Billinghurst, M. Tangible tiles: Design and evaluation of a tangible user interface in a collaborative tabletop setup. In *Proc. of OZCHI '06*, ACM (2006), 151–158.
29. Weiss, M., Wagner, J., Jansen, Y., Jennings, R., Khoshabeh, R., Hollan, J. D., and Borchers, J. Slap widgets: Bridging the gap between virtual and physical controls on tabletops. In *Proc. of CHI '09*, ACM (2009), 481–490.
30. Williams, C., Yang, X. D., Partridge, G., Millar-Usiskin, J., Major, A., and Irani, P. Tzee: Exploiting the lighting properties of multi-touch tabletops for tangible 3d interactions. In *Proc. of CHI '11*, ACM (2011), 1363–1372.
31. Willis, K., Brockmeyer, E., Hudson, S., and Poupyrev, I. Printed optics: 3d printing of embedded optical elements for interactive devices. In *Proc. of UIST '12*, ACM (2012), 589–598.