Changing the Appearance of Real-World Objects by Modifying Their Surroundings

David Lindlbauer[1], Jörg Müller[2], Marc Alexa[1]
[1] TU Berlin, Berlin, Germany
[2] Department of Computer Science, Aarhus University, Aarhus, Denmark

Figure 1. We present an approach for modifying the appearance of real-world objects by displaying virtual contents in their surroundings. We modify the size of object such as the book (*left*, enlarged in width and height). A set of keys is virtually raised and tilted by placing them on a rendered ramp (*middle*). The transparent bottle is augmented with virtual colors to remind users to stay hydrated. All graphics are rendered on a horizontal display which the objects are placed on. ***All images in the paper are photographs from our working prototype.***

ABSTRACT
We present an approach to alter the perceived appearance of physical objects by controlling their surrounding space. Many real-world objects cannot easily be equipped with displays or actuators in order to change their shape. While common approaches such as projection mapping enable changing the appearance of objects without modifying them, certain surface properties (e. g. highly reflective or transparent surfaces) can make employing these techniques difficult. In this work, we present a conceptual design exploration on how the appearance of an object can be changed by solely altering the space around it, rather than the object itself. In a proof-of-concept implementation, we place objects onto a tabletop display and track them together with users to display perspective-corrected 3D graphics for augmentation. This enables controlling properties such as the perceived size, color, or shape of objects. We characterize the design space of our approach and demonstrate potential applications. For example, we change the contour of a wallet to notify users when their bank account is debited. We envision our approach to gain in importance with increasing ubiquity of display surfaces.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI)

CHI 2017, May 06 – 11, 2017, Denver, CO, USA

ISBN 978-1-4503-4655-9/17/05. . . $15.00
http://dx.doi.org/10.1145/3025453.3025795

Author Keywords
dynamic appearance, augmented reality

INTRODUCTION
In the virtual world, from traditional desktop computing to virtual reality, changing the appearance of objects or interfaces is one of the main means to communicate information. Objects are altered in color for emphasizing them, they are hidden or revealed when needed, or resized to afford manipulation or communicate importance. Objects in *virtual* environments are easy to modify: research in computer graphics explored creating complex visual changes in real-time, for example through dynamic bump mapping [9] or environment mapping [10]. With the help of these techniques, arbitrary objects and alterations are achieved.

Research in HCI and computer graphics aimed at enabling similar techniques for objects in the real world. Projection mapping (or spatial augmented reality) enables changing the appearance of physical objects in real-time and on-demand (e. g. [4, 15, 35, 49]), without the need to actually modify the object. Projecting onto objects, however, is not always possible. Objects with transparent, dark or reflective surfaces are unsuited for projection, and would lead to drastically compromised image quality. Furthermore, projection mapping only allows for alterations *within the bounds of a target object*. The color or texture of an object may be changed, e. g. to optically shrink an object, however, enlargement is not possible due to the lack of projection surface (cf. [35]).

A different approach is to create objects directly from optically dynamic material (e. g. [36]), or equip them with in-situ displays (e. g. [45]). These approaches, as well as work on physically dynamic interfaces (cf. [29]) and from the field of ubiquitous computing (e. g. [60]), usually modify objects by including functionality through sensors, displays or optically dynamic materials during manufacturing. This, however, increases manufacturing complexity and later modifications would require tampering with the underlying hardware.

In this work, we propose a different approach. Instead of augmenting objects directly, we *change their appearance by altering their surrounding space.* This enables changing the appearance of objects without physical modification, and of objects with surface properties unsuitable for projection. This work provides a conceptual design exploration of our proposed approach and an initial proof-of-concept implementation.

We take inspiration from work on *visual illusions*, which typically alter the perception of an object through other objects that are present in its surroundings, similar to our approach. Furthermore, we build on computer graphics research on how objects are visually altered (e. g. through normal or environment maps). We create optically dynamic objects and contribute one additional technique (besides existing techniques such as projection mapping, shape-changing interfaces, and optically dynamic materials) for bridging the virtual and the real world.

We envision display surfaces to be ubiquitous in the future, for example through electronic wallpapers or projection (e. g. [48, 55]), so that objects are commonly surrounded by display surfaces. Our approach then allows augmenting objects e. g. for communicating information and status. Effects such as changes in size, position, or color are rendered perspective-corrected, which is enabled by tracking objects and users. As an example, we extend physical objects with virtual shapes such as the book in Figure 1 to increase its size. By showing virtual content such as platforms or ramps underneath an object, we can alter its perceived position, e. g. visually elevated by placing it on a platform. We change the color of objects by displaying differently colored areas in their close proximity. To decrease visual saliency and effectively "hide" objects from an observer, we blend them with the environment.

We demonstrate a proof-of-concept realization of our concept with a conventional tabletop display and an optical tracking system. We take inspiration from prior work on anamorphic graphics (e. g. [7]) and ubiquitous display surfaces (e. g. [48, 55]). We show the possibility of changing the perceived size, position, contour, color, or visibility of real-world objects. In our current implementation, objects are manually specified by users or are automatically recognized by our system based on predefined marker sets. We employ these effects in three scenarios: as ambient displays, for notifications, and for increased privacy. In the ambient display scenario, the color and position of existing objects (water bottle, medicine box, keys) are changed to communicate status. For displaying notifications, we change the perceived contour of a wallet to get dynamic spikes for indicating bank transactions. Lastly, by displaying colored areas in an object's surroundings we change its visibility to "hide" it from distant observers for increased privacy (we hide a phone on a user's desk).

Contributions

- We provide a design exploration of the concept of altering the appearance of existing, unmodified objects by displaying content in their surrounding space and characterize the design space of the approach.
- We provide a proof-of-concept implementation with a conventional display and an optical tracking system. It allows changing the appearance of objects without equipping them with additional output capabilities.
- We showcase three application scenarios demonstrating the versatility of our concept.

RELATED WORK

In this section we discuss relevant related work that examined direct and indirect augmentation of objects, as well as work from the fields of shape-changing interfaces and optically dynamic interfaces. Furthermore, we briefly review work on visual illusions that inspired us for this work.

Direct augmentation

Direct augmentation refers to augmenting objects by displaying graphics directly onto them, for example through projection mapping. With Shader Lamps [49], Raskar et al. changed the appearance of static objects through projection. Tangible 3D tabletop [15, 22] explored the connection of projection mapping and tabletop displays for augmenting tangible objects. Valbuena [58] and AntiVJ's Enghien [3] used projection mapping for emphasizing geometry, 3D effects, and transforming architecture. Bermano et al. [8] enriched the appearance of animatronic heads. Hettiarachchi and Wigdor [24], while focusing on haptic feedback, overlaid physical objects with graphics through a head-mounted display. Illuminating clay [47] augmented deformable surfaces for displaying volume data. Lindlbauer et al. [35] combined shape-changing interfaces with spatial augmented reality for extending the optical appearance of real-world interfaces.

With IllumiRoom [31], Jones et al. used projection mapping for projecting visual content around a display for increased immersion. In the RoomAlive [30] project, a room was augmented with projection for spatial augmented reality gaming. Bonanni et al. [12] augmented a kitchen with projection and framed their work in the context of hyper-reality [11]. They augmented existing objects with visual content for unobtrusive interaction such as a sink augmented with information on water temperature.

All these works focused either on direct augmentation of objects or extension with additional virtual contents, while our work focuses on extending existing real-world objects *without* direct projection. This allows us to create effects that are typically challenging to achieve such as enlarging objects as well as to augment objects with surface properties unsuited for projection (e. g. dark or transparent surfaces).

Indirect augmentation

Indirect augmentation refers to the augmentation of physical objects by displaying virtual content around them. With Urp [56] and I/O bulb [55], Underkoffler et al. augmented real-world objects with shadows for conveying information and to

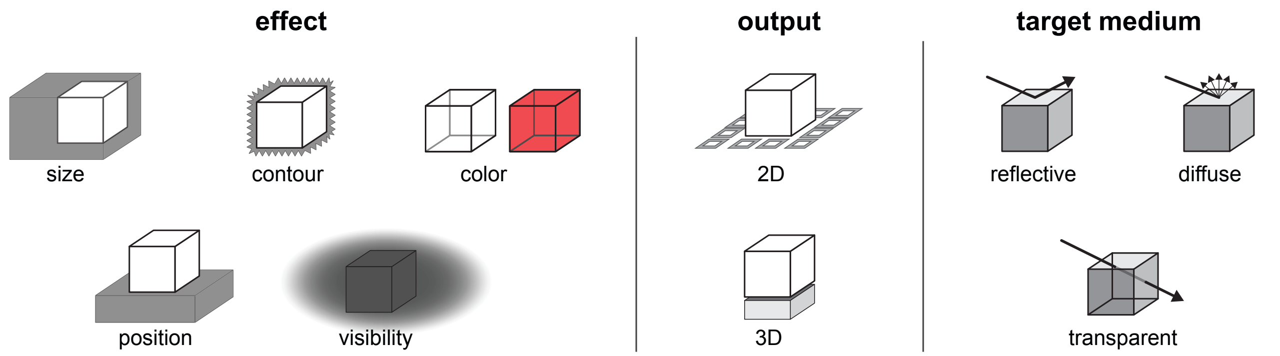

Figure 2. Design space for objects with dynamic appearance through virtual surroundings. Cubes illustrate the target objects.

enrich architectural models. This was developed in the context of the Luminous Room project [57], which aimed at unifying input and output of virtual contents in the real world, mostly through projection. On the same line, Naemura et al. [43] and Moon [40] projected virtual shadows of real-world objects for conveying a virtual light source.

These works enriched existing objects with illusions of shadows, focusing on communicating information such as the current time or augmentation for hedonic purposes. Our work aims at extending objects, i. e. their appearance, through more complex augmentations. By incorporating illusions such as extended size and dynamic contours we argue that the space of possible interactions is greatly extended.

Dynamic object appearance

Various approaches for altering the appearance by means of hardware modification exist. Olberding et al. [45] augmented objects with printed displays for altering their color and used them e. g. as information displays. Lindlbauer et al. [36] created transparency-controlled physical interfaces from optically dynamic material, which change their perceived shape through controlling the transparency of individual parts of an object. Alexa and Matusik [1] created objects as reliefs that change their appearance based on viewing angle. Other research focused on recreating realistic surface properties through dynamic reflectance functions (e. g. [17, 27, 28]).

Besides these optically dynamic interfaces, research on shape-changing interfaces altered the physical shape of devices for fulfilling functional [26] or hedonic aims [62], and exploration [29, 50]. They serve as input and output devices (e. g. [18, 34]) for applications such as telepresence or remote collaboration.

These works focus on in-situ modification of objects to allow dynamical alteration of optical properties. Consequently, the functionality of objects has to be known *before* manufacturing. If the desired functionality changes at a later stage, the objects have to be newly created. Our aim was to change the appearance of objects dynamically *without* modifying them. Additionally, our approach of visual augmentation does not require individual objects to contain power sources, displays or actuators for enabling their functionality.

Visual illusions

Wolf and Bäder [61] investigated inducing the illusion of a deformable surface using virtual deformation. Besides research from the fields of human–computer interaction and computer graphics, our work is inspired by work on visual illusions. We refer readers to different categorizations of visual illusions such as the work from Gregory et al. [19] and Changizi et al. [13], which we took as inspiration for exploring various effects such as size and color. Most classical illusions such as Ebbinghaus (change in perceived size), Hering (perceived line bend) or Chubb (change in perceived contrast) work well with simple 2D stimuli such as circles and lines. However, from our experience, the rather small effects observed even when using 2D stimuli (the effect magnitude of the classical Ebbinghaus illusion is around 20%, cf. [41]) vanish when employed with more complex real-world objects, which we elaborate on later in this paper. Nonetheless, from a broader point of view, we use these categorizations and create effects based on 3D renderings for dynamically altering e. g. the contour or perceived position of objects.

DYNAMIC OBJECT APPEARANCE THROUGH VIRTUAL SURROUNDINGS

We developed a design space for dynamically altering the appearance of objects by changing their surroundings, depicted in Figure 2. The design space is inspired by work on non-traditional displays [45], shape-changing interfaces [44, 50], and interfaces facilitating dynamic object appearance [35, 36], as well as taxonomies on visual illusions (e. g. [13, 19]).

Requirements

We created the design space with technologies such as (ubiquitous) display surfaces in mind. For any augmentation, the position and orientation of the object to be modified relative to the display needs to be known. Depending on the desired effect, we also need coarse or precise information on the object's properties, such as its color (transmission and/or reflectance) or shape (contours of full geometry). Most, but not all, effects require perspective rendering from the viewpoint of the user, which requires tracking the head or eye positions.

We place objects depicted throughout this paper onto a display. For simulating display surfaces that are included in furniture, we display a wooden surface texture in addition to the actual effects. We envision that in the future, displays will be ubiquitous, however currently our concept can only be achieved by turning a display into an actual desk. By including display surfaces into everyday furniture, objects that are surrounded by a display can easily be augmented using our approach.

We argue that the design space generalizes beyond technologies used in this paper, such as see-through augmented reality and projection. For all these technologies, also the environment *surrounding* an object can be visually altered, which is the main requirement of our concept.

Dimensions

The design space consists of three dimensions, which are *effect*, *output*, and *target medium* (Figure 2, *left*). Each effect has a *target*, which is the object it alters. The perception of the target is driven by the effect, which can be achieved with one or more types of output. The target medium influences which output and effects can be produced.

Effect

Size

The perceived size of an object is altered by virtually extending the target, i. e. displaying a larger virtual object with edges that are aligned to the target. This allows enlarging objects, as displayed in Figure 3. However, it does not allow decreasing the perceived volume of a target. In contrast, for methods like projection mapping a reduction in size is easily achievable (given a suitable projection target). For our approach, this effect works best for displaying 3D contents around an object, and also works for targets unsuitable for projection.

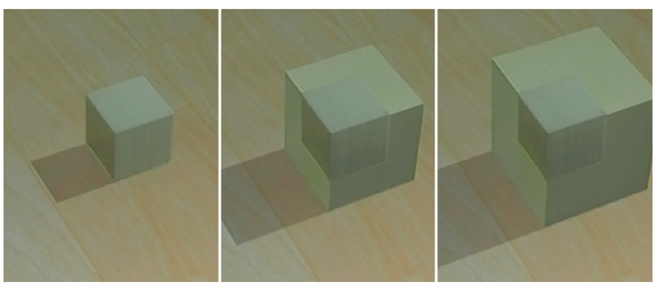

Figure 3. Effect of *size*. The cube is virtually extended to increase its size. Only the small cube (*left*) is an actual physical object, ground texture, shadows and extensions (*center* and *right*) are on-screen renderings.

Position

Our method alters the perceived position of a target, specifically it allows "raising" the target by adding virtual objects such as platforms underneath (see Figure 4). By rendering virtual ramps, the illusion of a tilted object can be induced (shown in Figure 1, *center*). The magnitude of this tilting effect, however, is relatively small from our experience due to other cues such as stereoscopic vision. Displaying shadows for physical and virtual objects adds to the realism of this effect.

Another method to induce changes in perceived position besides using solid virtual objects (e. g. the platform) is to add virtual shadows which make an object appear levitating on the surface (related to [43, 56]). This effect of perceived levitation, however, not only requires the addition of virtual shadows, but also a motion of the displayed ground texture dependent on the observer's current position. The ground texture is moved in concert with the motion of the observer to induce the illusion that the target is floating on the ground. We refer readers to the accompanying video for a demonstration of this and all other effects.

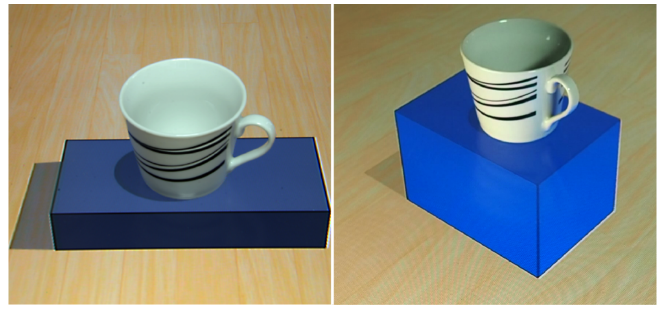

Figure 4. Effect of *position*. The cup is raised by placing it on a platform.

Contour

Similar to effects of size, the contour of an object can be altered, as shown in Figure 5. In the case that the target contains holes like the cup in Figure 5, those can be shrunk or fully closed. Similarly, the outline of the target can be modified, for example for notifications (e. g. the contour of a phone becomes "spiky").

This again highlights the complementary nature of our approach compared to projection mapping. For projection mapping (i. e. directly projecting onto objects), holes can be rendered if the background is known (i. e. video see-through, cf. [35]), however holes cannot be closed due to the lack of display surface. Our method allows to close holes in a surface, however it cannot render additional holes into the target.

Figure 5. Effect of *contour*. The cup is augmented with a virtual contour. The hole of the handle is shrunk (*left*) and the contour is altered (*right*).

Color

Modifying the color of an object can be an effective way for communicating information or status. The means of modification to change the color depend on the target medium. Transparent objects, as shown in Figure 1 (*right*), can be altered by displaying differently colored areas *behind* objects. The notion of "behind" depends on the viewing position and needs to be adapted according to the user's head position.

The color of non-transparent surfaces is altered by displaying colored areas around the target, depicted in Figure 8. This allows for exploiting light coming from the display surface, effectively shining colored light onto objects. This effect is increased with the surface reflectance of the target object. The process of finding the corresponding area on which color has to be displayed for covering the whole target can be compared to ray tracing. Since the geometry of the target is know, rays can be traced from the observer's position to the target and follow their reflection. The area covered by the rays bouncing from the surface of the target corresponds to the minimum area that needs to be colored to change the color of the target.

Visibility

By extending the uniformly colored areas of a target, its visual saliency can be altered. As shown in Figure 6, the outline of the phone is less visible by displaying a black area around it. The surface of the target is extended, drawing attention away from the actual target. This is useful in situations where users don't want objects to be immediately visible, for example drawing attention away from the phone when briefly leaving their desk. For targets with higher frequency textures, the textures can also be extended. We also call this effect of altering the surroundings to hide objects the *inverse camouflage effect*. In contrast to classical camouflage techniques where the color of a target is altered, we alter the surrounding space to visually hide the target.

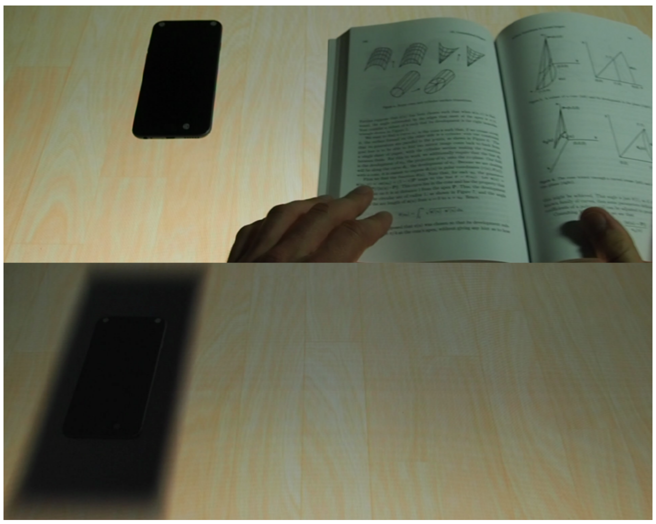

Figure 6. Effects of *visibility*. The target (phone, *top left*) is hidden by displaying matching color in its surroundings (*bottom*).

Output

The dimension *output* refers to the type of rendering that is employed for displaying effects, which can be either in 2D or 3D. While all renderings are obviously 2D (i. e. on a display), this dimension refers to the perception of virtual contents by the observer. 2D output, as used in classical illusions, can yield changes in color and visibility (Figure 8 and 6, respectively). For observers, these effects are flat 2D stimuli, without any notion of 3D. This means that the vanishing point is solely dependent on the observer's location. Since no perspective-corrected rendering is needed, 2D effects have the benefit that only the target's approximate position and size have to be known, not its exact geometry or the user's position.

3D output (off-axis view shown in Figure 7) is required to correctly align physical and virtual objects when creating effects such as changes in contour, size or position. Thus, those effects are created with respect to the observer's location as well as with knowledge of the object's position and geometry.

3D output aims at being indistinguishable from targets, which is challenging with current displays due constraints in color and resolution (our current display only has a resolution of about 38 pixels per inch). We discuss technical requirements for high quality illusions in the implementation section.

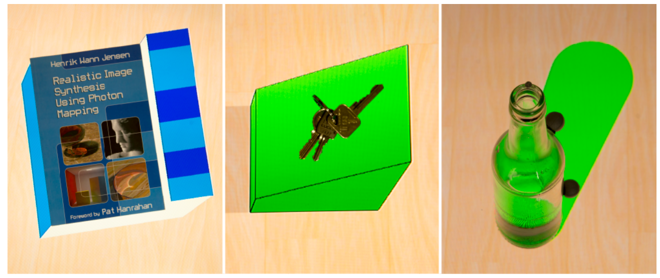

Figure 7. Top view (off-axis) of effects of size, position and color. All graphics, including the wooden surface texture, around the targets (book, keys, bottle) are displayed on a 42 inch horizontal display. Graphics are rendered perspective-corrected to appear 3D.

Target medium

We categorize three different target media for our approach. The medium governs which effects can be achieved as well as their effectiveness. Targets with *diffuse* surface are suitable for effects that do not rely on reflection and transparency, such as changes in size, contour or position. Effects of color (shown in Figure 8 with a reflective target), are possible, however their effect is weaker than for other media when employed on a target with diffuse surface. This is because effects of color rely on directed reflection, which is weak for diffuse objects.

Targets with *reflective* surface properties such as the green cup in Figure 8 (*bottom*) are suitable for changes in size, position or contour, and also suitable for effects of color that are based on reflection.

Figure 8. Effect of *color* with an reflective opaque surface. The reflection on the surface in combination with the displayed color alter the target's color.

Lastly, targets with *transparent* surface are especially suitable for effects of color. Altering the color of transparent surfaces is highly challenging for techniques that rely on direct projection. Our approach results in the perception of a dynamically colored target, as shown in Figure 1 (*right*), although it really is the surface *behind* the objects that is modified.

IMPLEMENTATION

Our system uses a passive-marker optical tracking system (OptiTrack), and a control application written in C++ with openFrameworks[1] for rendering. Graphics are displayed on a horizontally-placed 42 inch LCD screen (Philips 42PF7621D, resolution 1366 × 768 pixels, 38 pixels per inch). We chose this display for its low parallax, i. e. there is little space between objects placed on the display and the virtual content.

[1] http://openframeworks.cc/

Our system tracks the display surface, the user's head, and objects placed on the display. For perspective-corrected rendering we match the virtual camera's position to the tracked head position. The view frustum is modified so that the corner points of the near and far plane align with the corners of the tracked display, which is commonly referred to as fish-tank augmented reality (cf. [37, 53]), used for example for 3D tabletop displays [23, 42] or 3D see-through displays [25].

The virtual objects surrounding the real-world objects were designed to match the shape of the target objects. Coarse 3D shapes were created programmatically or 3D modeled as proxies for the physical objects (e. g. a simple box for the wallet in Figure 10). This is necessary since effects of size, contour and color (for transparent objects) require knowledge of a target's geometry. Colors were manually adjusted to decrease the perceived difference between the target and the augmentation. Objects placed on the display are recognized based on their markers, configured as predefined marker sets (rigid bodies) in the OptiTrack control software.

Limitations of virtual extensions

For effects of size, target objects are visually extended with virtual content that is aligned to the target. This, however, only works if the area of the target that should be extended is facing away from the observer. Consider an observer's viewing direction $\vec{v} \in \mathbb{R}^3$ that is pointing towards a face on the surface, whose normal is denoted by $\vec{n} \in \mathbb{R}^3$. We then calculate the angle α between the two vectors $\vec{v}$ and $\vec{n}$. The extension can only be display correctly if $|\alpha| < 90°$, i. e. the virtual content is displayed without being occluded by the target, as depicted in Figure 9, *left*. If the angle is larger than 90°, the augmentation is occluded by the target, effectively hindering correctly displaying the virtual extension, illustrated in Figure 9, *right*. In our implementation, if α is approaching 90°, the extension is set to zero length, effectively disabling the illusion of extended size for the particular face. We chose this method to not break the illusion of extension.

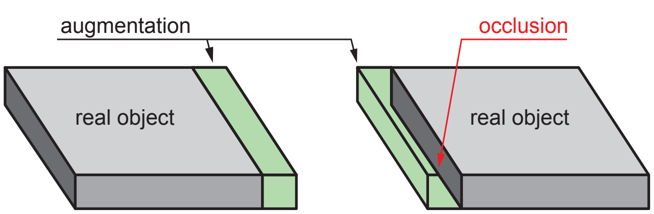

Figure 9. Extending a target only works if the normal of the extended side faces away from the observer (*left*). If the angle formed by the normal of the extended face and the viewing direction is larger than 90°, the target occludes the virtual content (*right*).

Technical considerations

Our proof-of-concept implementation does not provide the visual fidelity to make virtual content and real-world objects undistinguishable. In the following, we discuss the most important aspects which systems would need to provide to allow for such high quality visual effects.

Tracking the user's eye position for displaying 3D contents

Accurately displaying 3D contents requires providing two different images for the user, one for each eye. Therefore, not only head tracking but eye-position tracking is needed. This aspect is especially important when aligning virtual 3D content with real-world objects when viewed from close proximity (distance < 1.5 m). When only a single image is provided, vergence discrepancies may arise, i. e. the virtual and real-world object are only correctly aligned for one eye. Autostereoscopic displays (e. g. [16, 46]) overcome these challenges, for example by tracking user's eyes with a retroreflective camera and providing two different images with an active shutter [46]. This approach can be extended to multiple users with a multiview parallax display (e. g. [2]).

Recognizing objects to allow for augmentation

To enable augmentation, objects that are situated in a user's environment have to be detected and, if needed, recognized. Detecting objects for example through segmentation has been demonstrated using commodity depth cameras, e. g. by Karpathy et al. [32] or Valentin et al. [59]. The resulting data can serve as input for recognition systems, e. g. model-based approaches such as by Mian et al. [38]. Besides camera-based sensing techniques, it is possible to include sensors directly into objects (e. g. using RFID [39], or optical markers like in our prototype) and combine this with position tracking. All these approaches require a priori knowledge of the objects that should be augmented (i. e. their shape, color, texture, illumination).

Matching color & material of virtual and real-world objects

Accurately determining the texture and other material properties such as transparency of physical objects can be challenging. While a camera is sufficient for simple color tracking, more complex surface properties such as reflectance of transparency are not captured. Tracking the reflectance and transparency of objects can be performed e. g. using active LED-based approaches ([5, 21, 51]). For these approaches, objects are illuminated with LEDs with different wavelengths for gathering their optical properties. While those systems achieve high accuracy, specialized hardware is required. Alternatively, camera-based machine learning approaches can be used (e. g. using SVM classifiers [52]). Those provide a good balance between hardware requirements and fidelity of the results. Due to changes in ambient illumination, a closed-loop approach for capturing and displaying colors (e. g. [20]) is needed for all approaches.

APPLICATIONS

Application 1: Ambient displays

We created three different ambient display applications. First, our system changes the perceived color of a transparent water bottle from green to yellow to red dependent on the time elapsed since the user drank last (see Figure 1, *right*). Secondly, we augment a pack of medicine with a virtual platform. The platform raises slowly to convey an elevated position to remind users of taking their medication. Finally, we display a virtual platform underneath a set of keys (as in Figure 1, *center*). When the user leaves the desk, one side of the platform is lowered, thus the platform becomes a ramp. This virtual ramp should remind users to not forget their keys. All these perceptual changes are achieved *without actually modifying the object* and aim at unobtrusively capturing the user's attention.

Application 2: Notifications

We use virtual contents for displaying notifications to users. We augment a wallet (shown in Figure 10) for helping users keep track of their bank transactions, inspired by the Proverbial Wallet by Kestner et al. [33]. The wallet changes its contour every time money is withdrawn from the account, for example from monthly subscriptions or transactions on a shared credit card. The shape, size and speed of the dynamic contour correlate with the amount spent, i. e. the higher the amount, the larger and faster the notification gets.

Figure 10. The wallet changes its contour when money is debited from the user's bank account.

Application 3: Privacy

Users can hide objects in their workplace by virtually blending them into the surrounding space. Our system detects objects based on their markers placed in the environment and modifies the color of the surroundings. This way, objects draw less visual attention since their color or contour becomes less salient. As an example, a phone placed on a desk (see Figure 6) is less easily visible from a distance. We exploit the fact that larger, uni-color areas (i. e. the target and the area around it) potentially attract less attention than individual objects with sharp contours and distinct colors (cf. [54]).

PRELIMINARY EXPERIMENTATION

In order to gather preliminary insights if users are able to perceive our proposed effects, we performed a small scale experiment. We placed a 3D printed cube (side length 40 mm, known to participants) on a virtual platform (see Figure 11) and randomly varied the height of the platform between 10 mm and 110 mm. Eight participants (3 female, all staff from local university) were asked to estimate the height of the virtual platform in 10 trials each.

The data of these 80 trials is well approximated by a linear model, showing a mean estimation error of 14.5% (SD=11.5%), i. e. 11.3 mm ($SD = 10.4$ mm). A simple linear regression was calculated to predict participants' estimate based on the actual height of the virtual platform. A significant regression equation was found ($F_{1,14} = 486.585$, $p < .001$), with an R^2 of .862. Participants' estimated height is equal to $3.388 + 1.113$ (actual height), measured in millimeters. This shows that participants perceived the desired effect of an elevated physical object and that the desired effect size strongly correlates with its perception. While none of our participants were 'fooled' by the effects due to the low fidelity of current implementation, they were able to perceive the desired effect.

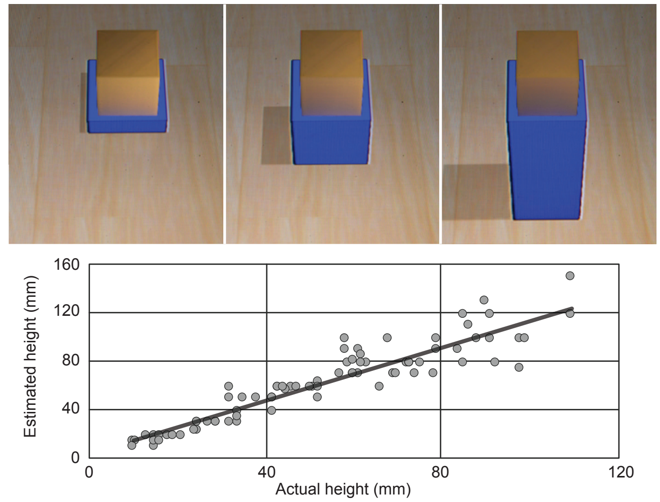

Figure 11. ***Top:*** **Participants were asked to estimate the randomly varied height of the virtual platform underneath the white 3D printed cube (here from left to right: 10 mm, 40 mm, 100 mm).** ***Bottom:*** **Data collected in our preliminary experiment with fitted linear model.**

DISCUSSION

Altering existing objects and devices through virtual illusions, or more generally, through displaying contents around them has a number of benefits compared to existing approaches, summarized in Table 1. Direct augmentation techniques such as projection mapping allow changing the appearance of objects, however only if the objects exhibit surface properties that are suitable for projection. Many works on augmented reality focused on the *addition* of virtual contents (e. g. rendering virtual characters) to real scenes (e. g. [6, 25]). Our work focused on changing existing objects, for example changing their color or perceived size. Shape-changing interfaces require including the desired functionality during manufacturing, however modification of existing devices is not always feasible. Additionally, changes in perceived size such as a mechanical increase in volume can be challenging to achieve. Transparency-controlled interfaces [36] allow for alterations of volume and visibility, however they also have to be manufactured with these functionalities in mind. Furthermore, they do not allow changing the color of targets and their ability to induce the illusion of changed position is limited.

	Our approach	**Projection mapping**	**SCI**	**TCI**
Size	larger	(smaller)	✓	✓
Position	✓	×	✓	×
Contour	✓	(✓)	✓	×
Color	✓	(✓)	×	×
Visibility	✓	(✓)	×	✓

Table 1. Comparison of different techniques: our approach, projection mapping, shape-changing interfaces (SCI), and transparency-controlled interfaces (TCI, [36]). Effects created with projection mapping are marked in brackets since they require a suitable projection surface.

However, our work yields limitations in terms of visual changes that are possible to achieve as well as providing feedback other than of visual nature.

Tactile limitations

Our proposed concept does not provide any dynamic tactile sensation. While it is still suitable for interactions where no tactile feedback is needed (e. g. ambient displays, distant interaction, peripheral interaction), it lacks the tactile qualities of shape-changing interfaces. However, it has benefits in terms of rendering possibilities (e. g. changing the perceived size).

Visual fidelity and stereo vision

Making virtual contents indistinguishable from physical objects is challenging, as discussed above on a technical level. Systems aiming at providing high quality object augmentation have to meet requirements in terms of *display quality* (resolution and capability to accurately reproduce materials), *stereo rendering* as well as *system responsiveness*. Not meeting one of those requirements will most likely break perceptual effects. We aimed at providing an initial design exploration of our proposed approach. Our current prototype does not aim at 'fooling' users into believing that the illusions are real, but at conveying information through visual effects.

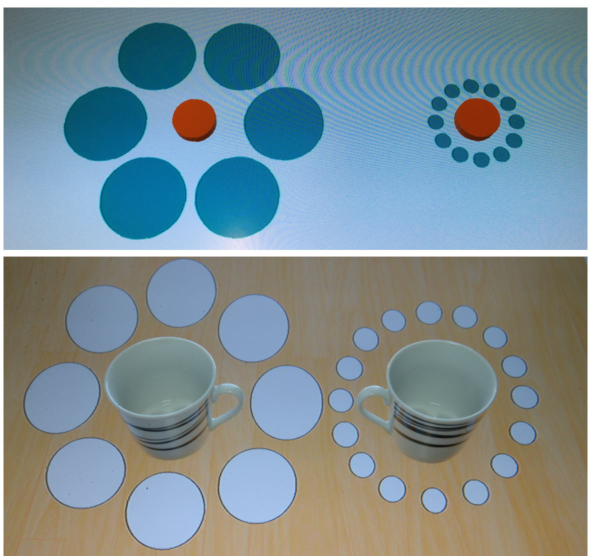

Figure 12. The Ebbinghaus illusion for a simple target (puck, *top*) and a geometrically more complex target (cup, *bottom*). Although both pucks have exactly the same size (36 mm), the right one appears to be larger. The illusion was not present for more complex objects like the cup.

CLASSICAL VISUAL ILLUSIONS IN 3D

We see our approach related to work on visual illusions, which typically have a target object that is perceptually altered by surrounding objects. However, even typically strong visual illusions such as the Ebbinghaus illusion (see Figure 12) only have an effect magnitude of about 20% (cf. [41]). Other illusions such as the Watercolor or the Delbouef illusion yield even more subtle effects (cf. [13]). Illusions such as Ponzo or Hering work well in 2D since they rely on a mismatch of 2D and 3D visual sensation ("errors in perception", [19]).

When applying these illusions to complex 3D stimuli, however, effects such as increase in size did not emerge in our initial experiments. As shown in Figure 12 (*top*), the Ebbinghaus illusion when used on a simple 3D printed cylinder triggers the illusion that the right target is larger than the left one (both have the same size). When used on geometrically more complex objects like the cup in Figure 12 (*bottom*), the illusion is not present. The same is true e. g. for contrast illusions like the Chubb illusion [14] (or *simultaneous contrast effect*), as illustrated in Figure 13. The Chubb illusion yields a change in perceived contrast when a target is surrounded by differently colored area (e. g. lighter background yields darker object).

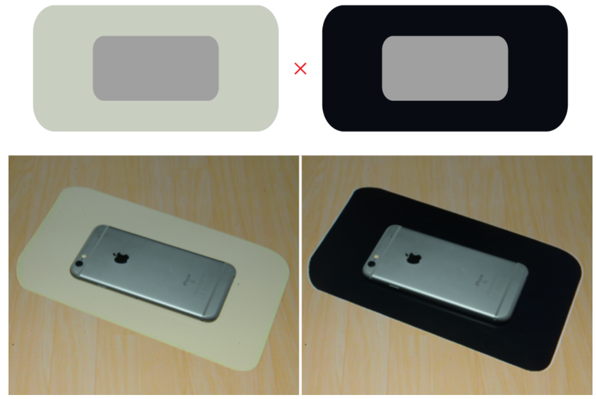

Figure 13. Comparison of the classical Chubb illusion with 2D primitives (*top*) and real-world objects (*bottom*). Objects in the center have the same color. For the classical illusion, the left object in the center appears darker, especially when focusing on the red cross in the center. This effect is highly decreased for real-world objects.

These observations lead us to believe that knowledge from classical illusions in 2D is not easily transferable to complex 3D stimuli. Therefore, we resorted to a more complex environment using techniques from computer graphics (such as perspective-corrected 3D rendering) for creating the *illusion* of dynamic appearance. We emphasize that this does *not* necessarily mean that classical illusions do not work in 3D. We note, however, that it might require very careful design of (new) illusions and parameter tuning before effects emerge. We believe more research is needed to understand the effect of classical illusions effective in 'flat' environments in the context of genuinely 3D stimuli.

CONCLUSION

We presented a design exploration of an approach for altering the appearance of a physical object by displaying content in its surrounding space. Our approach does not require modifying an object's shape and it is applicable even when projection mapping is not possible. We achieve different effects such as changes in perceived size, color, position or contour. The perceptual change is very effective, in particular considering that the actual real object is unaltered, and it works with virtually any type of object and material. The effect may be used in various applications, of which we show ambient information displays, notifications, and increased privacy as prototypical examples. In conjunction with other modes of altering the perception of reality our approach is suitable in a much wider context, which we would gladly explore in the future.

ACKNOWLEDGEMENTS

We want to thank Alexandra Ion, Christian Lessig and Philipp Herholz for feedback and discussion. This work has been supported by the ERC through grant ERC-2010-StG 259550 ("XSHAPE").

REFERENCES

1. Marc Alexa and Wojciech Matusik. 2010. Reliefs As Images. *ACM Trans. Graph.* 29, 4, Article 60 (July 2010), 7 pages. http://doi.acm.org/10.1145/1778765.1778797

2. Thomas Annen, Wojciech Matusik, Hanspeter Pfister, Hans-Peter Seidel, and Matthias Zwicker. 2006. Distributed rendering for multiview parallax displays. In *Proceedings SPIE 6055, Stereoscopic Displays and Virtual Reality Systems XIII*, Vol. 6055. http://dx.doi.org/10.1117/12.650171

3. AntiVJ. 2009. Enghien. (2009). Retrieved September 17, 2016 from http://antivj.com/enghien/.

4. Deepak Bandyopadhyay, Ramesh Raskar, and Henry Fuchs. 2001. Dynamic Shader Lamps: Painting on Movable Objects. In *Proceedings of the IEEE and ACM International Symposium on Augmented Reality (ISAR '01)*. IEEE Computer Society, Washington, DC, USA. http://doi.org/10.1109/ISAR.2001.970539

5. Moshe Ben-Ezra, Jiaping Wang, Bennett Wilburn, Xiaoyang Li, and Le Ma. 2008. An LED-only BRDF measurement device. In *2008 IEEE Conference on Computer Vision and Pattern Recognition (CVPR '08)*. 1–8. http://dx.doi.org/10.1109/CVPR.2008.4587766

6. Hrvoje Benko, Ricardo Jota, and Andrew Wilson. 2012. MirageTable: Freehand Interaction on a Projected Augmented Reality Tabletop. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 199–208. http://doi.acm.org/10.1145/2207676.2207704

7. Hrvoje Benko, Andrew D. Wilson, and Federico Zannier. 2014. Dyadic Projected Spatial Augmented Reality. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 645–655. http://doi.acm.org/10.1145/2642918.2647402

8. Amit Bermano, Philipp Brüschweiler, Anselm Grundhöfer, Daisuke Iwai, Bernd Bickel, and Markus Gross. 2013. Augmenting Physical Avatars Using Projector-based Illumination. *ACM Trans. Graph.* 32, 6, Article 189 (Nov. 2013), 10 pages. http://doi.acm.org/10.1145/2508363.2508416

9. James F. Blinn. 1978. Simulation of Wrinkled Surfaces. In *Proceedings of the Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '78)*. ACM, New York, NY, USA, 286–292. http://doi.acm.org/10.1145/800248.507101

10. James F. Blinn and Martin E. Newell. 1976. Texture and Reflection in Computer Generated Images. *Commun. ACM* 19, 10 (Oct. 1976), 542–547. http://doi.acm.org/10.1145/360349.360353

11. Leonardo Bonanni. 2006. Ambient Intelligence in Everyday Life. Springer-Verlag, Berlin, Heidelberg, Chapter Living with Hyper-reality, 130–141. http://dx.doi.org/10.1007/11825890_6

12. Leonardo Bonanni, Chia-Hsun Lee, and Ted Selker. 2005. Cooking with the Elements: Intuitive Immersive Interfaces for Augmented Reality Environments. In *IFIP TC13 International Conference 2005, Lecture Notes in Computer Science, Vol 3585. (INTERACT '05)*. Springer, Berlin, Heidelberg, 1022–1025. http://dx.doi.org/10.1007/11555261_95

13. Mark A. Changizi, Andrew Hsieh, Romi Nijhawan, Ryota Kanai, and Shinsuke Shimojo. 2008. Perceiving the Present and a Systematization of Illusions. *Cognitive Science* 32, 3 (2008), 459–503. http://dx.doi.org/10.1080/03640210802035191

14. Charles Chubb, George Sperling, and Joshue A. Solomon. 1990. Texture interactions determine perceived contrast. *Proceedings of the National Academy of Sciences of the United States of America* 87, 3 (1990), 9631–9635.

15. Peter Dalsgaard and Kim Halskov. 2011. 3D Projection on Physical Objects: Design Insights from Five Real Life Cases. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 1041–1050. http://doi.acm.org/10.1145/1978942.1979097

16. Neil A. Dodgson. 2005. Autostereoscopic 3D Displays. *Computer* 38, 8 (Aug 2005), 31–36. http://dx.doi.org/10.1109/MC.2005.252

17. Yue Dong, Jiaping Wang, Fabio Pellacini, Xin Tong, and Baining Guo. 2010. Fabricating Spatially-varying Subsurface Scattering. *ACM Trans. Graph.* 29, 4, Article 62 (July 2010), 10 pages. http://doi.acm.org/10.1145/1778765.1778799

18. Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: Dynamic Physical Affordances and Constraints Through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 417–426. http://doi.acm.org/10.1145/2501988.2502032

19. Richard L. Gregory. 1997. Knowledge in perception and illusion. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 352, 1358 (1997), 1121–1127. http://dx.doi.org/10.1098/rstb.1997.0095

20. Michael D. Grossberg, Harish Peri, Shree K. Nayar, and Peter N. Belhumeur. 2004. Making one object look like another: controlling appearance using a projector-camera system. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR '04)*. http://dx.doi.org/10.1109/CVPR.2004.1315067

21. Jinwei Gu and Chao Liu. 2012. Discriminative illumination: Per-pixel classification of raw materials based on optimal projections of spectral BRDF. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR '12)*. 797–804. http://dx.doi.org/10.1109/CVPR.2012.6247751

22. Kim Halskov, Peter Dalsgaard, and Louise Bak Stolze. 2014. Analysing Engaging Experiences with a Tangible

3D Tabletop. In *Proceedings of the Conference on Advances in Computer Entertainment Technology (ACE '14)*. ACM, New York, NY, USA, Article 29, 10 pages. http://doi.acm.org/10.1145/2663806.2663831

23. Mark Hancock, Miguel Nacenta, Carl Gutwin, and Sheelagh Carpendale. 2009. The Effects of Changing Projection Geometry on the Interpretation of 3D Orientation on Tabletops. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '09)*. ACM, New York, NY, USA, 157–164. http://doi.acm.org/10.1145/1731903.1731934

24. Anuruddha Hettiarachchi and Daniel Wigdor. 2016. Annexing Reality: Enabling Opportunistic Use of Everyday Objects As Tangible Proxies in Augmented Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1957–1967. http://doi.acm.org/10.1145/2858036.2858134

25. Otmar Hilliges, David Kim, Shahram Izadi, Malte Weiss, and Andrew Wilson. 2012. HoloDesk: Direct 3D Interactions with a Situated See-through Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 2421–2430. http://doi.acm.org/10.1145/2207676.2208405

26. Oren Horev. 2006. 'Talking to the Hand' An exploration into shape shifting objects and morphing interfaces. (2006). Master's thesis.

27. Matthias B. Hullin, Ivo Ihrke, Wolfgang Heidrich, Tim Weyrich, Gerwin Damberg, and Martin Fuchs. 2013. Computational Fabrication and Display of Material Appearance. In *EUROGRAPHICS '13 State-of-the-Art Report*. http://dx.doi.org/10.2312/conf/EG2013/stars/137-153

28. Matthias B. Hullin, Hendrik P. A. Lensch, Ramesh Raskar, Hans-Peter Seidel, and Ivo Ihrke. 2011. Dynamic Display of BRDFs. *Computer Graphics Forum* 30, 2 (2011), 475–483. http://dx.doi.org/10.1111/j.1467-8659.2011.01891.x

29. Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials. *interactions* 19, 1 (Jan. 2012), 38–51. http://doi.acm.org/10.1145/2065327.2065337

30. Brett Jones, Rajinder Sodhi, Michael Murdock, Ravish Mehra, Hrvoje Benko, Andrew Wilson, Eyal Ofek, Blair MacIntyre, Nikunj Raghuvanshi, and Lior Shapira. 2014. RoomAlive: Magical Experiences Enabled by Scalable, Adaptive Projector-camera Units. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 637–644. http://doi.acm.org/10.1145/2642918.2647383

31. Brett R. Jones, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2013. IllumiRoom: Peripheral Projected Illusions for Interactive Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 869–878. http://doi.acm.org/10.1145/2470654.2466112

32. A. Karpathy, S. Miller, and Li Fei-Fei. 2013. Object discovery in 3D scenes via shape analysis. In *2013 IEEE International Conference on Robotics and Automation*. 2088–2095. http://dx.doi.org/10.1109/ICRA.2013.6630857

33. John Kestner, Daniel Leithinger, Jaekyung Jung, and Michelle Petersen. 2009. Proverbial Wallet: Tangible Interface for Financial Awareness. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09)*. ACM, New York, NY, USA, 55–56. http://doi.acm.org/10.1145/1517664.1517683

34. Daniel Leithinger, David Lakatos, Anthony DeVincenzi, Matthew Blackshaw, and Hiroshi Ishii. 2011. Direct and Gestural Interaction with Relief: A 2.5D Shape Display. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology (UIST '11)*. ACM, New York, NY, USA, 541–548. http://doi.acm.org/10.1145/2047196.2047268

35. David Lindlbauer, Jens Emil Grønbæk, Morten Birk, Kim Halskov, Marc Alexa, and Jörg Müller. 2016a. Combining Shape-Changing Interfaces and Spatial Augmented Reality Enables Extended Object Appearance. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 791–802. http://doi.acm.org/10.1145/2858036.2858457

36. David Lindlbauer, Jörg Müller, and Marc Alexa. 2016b. Changing the Appearance of Physical Interfaces Through Controlled Transparency. In *Proceedings of the Annual ACM Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA. http://doi.acm.org/10.1145/2984511.2984556

37. Michael McKenna. 1992. Interactive Viewpoint Control and Three-dimensional Operations. In *Proceedings of the 1992 Symposium on Interactive 3D Graphics (I3D '92)*. ACM, New York, NY, USA, 53–56. http://doi.acm.org/10.1145/147156.147163

38. Ajmal S. Mian, Mohammed Bennamoun, and Robyn Owens. 2006. Three-Dimensional Model-Based Object Recognition and Segmentation in Cluttered Scenes. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 28, 10 (Oct 2006), 1584–1601. http://dx.doi.org/10.1109/TPAMI.2006.213

39. Florian Michahelles, Frederic Thiesse, Albrecht Schmidt, and John R. Williams. 2007. Pervasive RFID and Near Field Communication Technology. *IEEE Pervasive Computing* 6, undefined (2007), 94–96, c3. http://dx.doi.org/10.1109/MPRV.2007.64

40. John Y. Moon. 2010. Augmented Shadow. (2010). Retrieved September 12, 2016 from http://cargocollective.com/joonmoon/Augmented-Shadow.

41. Ryan E. B. Mruczek, Christopher D. Blair, Lars Strother, and Gideon P. Caplovitz. 2015. The Dynamic Ebbinghaus: motion dynamics greatly enhance the classic contextual size illusion. *Frontiers in Human Neuroscience* 9, 77 (2015). http://doi.org/10.3389/fnhum.2015.00077

42. Miguel A. Nacenta, Mark Hancock, Carl Gutwin, and Sheelagh Carpendale. 2016. The Effects of Changing Projection Geometry on Perception of 3D Objects on and Around Tabletops. *ACM Trans. Comput.-Hum. Interact.* 23, 2, Article 11 (May 2016), 54 pages. http://doi.acm.org/10.1145/2845081

43. Takeshi Naemura, Takuya Nitta, Atsushi Mimura, and Hiroshi Harashima. 2002. Virtual shadows-enhanced interaction in mixed reality environment. In *Virtual Reality, 2002. Proceedings. IEEE*. 293–294. http://dx.doi.org/10.1109/VR.2002.996545

44. Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. 2015. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology (UIST '15)*. ACM, New York, NY, USA, 333–339. http://doi.acm.org/10.1145/2807442.2807452

45. Simon Olberding, Michael Wessely, and Jürgen Steimle. 2014. PrintScreen: Fabricating Highly Customizable Thin-film Touch-displays. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 281–290. http://doi.acm.org/10.1145/2642918.2647413

46. Ken Perlin, Salvatore Paxia, and Joel S. Kollin. 2000. An Autostereoscopic Display. In *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '00)*. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 319–326. http://dx.doi.org/10.1145/344779.344933

47. Ben Piper, Carlo Ratti, and Hiroshi Ishii. 2002. Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02)*. ACM, New York, NY, USA, 355–362. http://doi.acm.org/10.1145/503376.503439

48. Ramesh Raskar, Greg Welch, Matt Cutts, Adam Lake, Lev Stesin, and Henry Fuchs. 1998. The Office of the Future: A Unified Approach to Image-based Modeling and Spatially Immersive Displays. In *Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '98)*. ACM, New York, NY, USA, 179–188. http://doi.acm.org/10.1145/280814.280861

49. Ramesh Raskar, Greg Welch, Kok-Lim Low, and Deepak Bandyopadhyay. 2001. Shader Lamps: Animating Real Objects With Image-Based Illumination. In *Proceedings of the 12th Eurographics Workshop on Rendering Techniques*. Springer-Verlag, London, UK, UK, 89–102. http://dx.doi.org/10.1007/978-3-7091-6242-2_9

50. Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-changing Interfaces: A Review of the Design Space and Open Research Questions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 735–744. http://doi.acm.org/10.1145/2207676.2207781

51. Munehiko Sato, Shigeo Yoshida, Alex Olwal, Boxin Shi, Atsushi Hiyama, Tomohiro Tanikawa, Michitaka Hirose, and Ramesh Raskar. 2015. SpecTrans: Versatile Material Classification for Interaction with Textureless, Specular and Transparent Surfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2191–2200. http://dx.doi.org/10.1145/2702123.2702169

52. Lavanya Sharan, Ce Liu, Ruth Rosenholtz, and Edward H. Adelson. 2013. Recognizing Materials Using Perceptually Inspired Features. *International Journal of Computer Vision* 103, 3 (2013), 348–371. http://dx.doi.org/10.1007/s11263-013-0609-0

53. Ian Stavness, Billy Lam, and Sidney Fels. 2010. pCubee: A Perspective-corrected Handheld Cubic Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 1381–1390. http://doi.acm.org/10.1145/1753326.1753535

54. Anne M. Treisman and Garry Gelade. 1980. A feature-integration theory of attention. *Cognitive Psychology* 12, 1 (1980), 97 – 136. http://dx.doi.org/10.1016/0010-0285(80)90005-5

55. John Underkoffler and Hiroshi Ishii. 1998. Illuminating Light: An Optical Design Tool with a Luminous-tangible Interface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '98)*. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 542–549. http://dx.doi.org/10.1145/274644.274717

56. John Underkoffler and Hiroshi Ishii. 1999. Urp: A Luminous-tangible Workbench for Urban Planning and Design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '99)*. ACM, New York, NY, USA, 386–393. http://doi.acm.org/10.1145/302979.303114

57. John Underkoffler, Brygg Ullmer, and Hiroshi Ishii. 1999. Emancipated Pixels: Real-world Graphics in the Luminous Room. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99)*. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 385–392. http://dx.doi.org/10.1145/311535.311593

58. Pablo Valbuena. 2008. Augmented Sculpture. (2008). Retrieved September 17, 2015 from http://www.pablovalbuena.com/selectedwork/augmented-sculpture-v1/.

59. Julien Valentin, Vibhav Vineet, Ming-Ming Cheng, David Kim, Jamie Shotton, Pushmeet Kohli, Matthias Nießner, Antonio Criminisi, Shahram Izadi, and Philip Torr. 2015. SemanticPaint: Interactive 3D Labeling and Learning at Your Fingertips. *ACM Trans. Graph.* 34, 5, Article 154 (Nov. 2015), 17 pages. http://dx.doi.org/10.1145/2751556

60. Mark Weiser. 1999. The Computer for the 21st Century. *SIGMOBILE Mob. Comput. Commun. Rev.* 3, 3 (1999), 3–11. http://doi.acm.org/10.1145/329124.329126

61. Katrin Wolf and Timm Bäder. 2015. Illusion of Surface Changes Induced by Tactile and Visual Touch Feedback. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 1355–1360. http://doi.acm.org/10.1145/2702613.2732703

62. Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 13–22. http://doi.acm.org/10.1145/2501988.2502037