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CleAR Sight: Exploring the Potential of Interacting with Transparent Tablets in Augmented Reality

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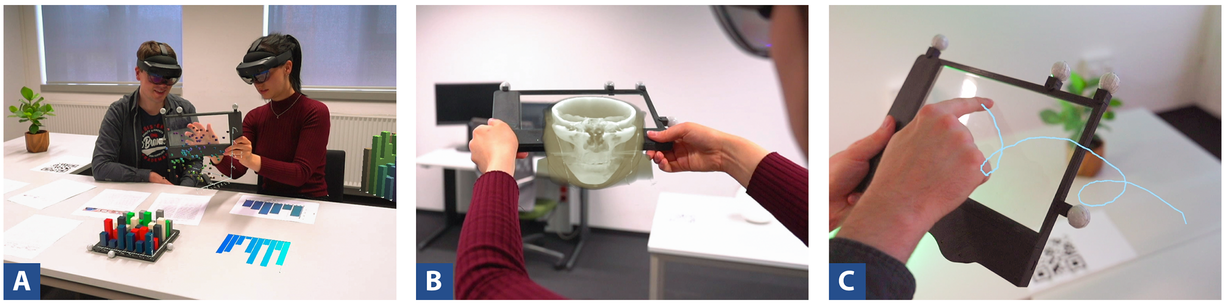

Figure 1: The CleAR Sight research platform allows multiple people to use a touch-enabled, transparent interaction panel and perform tasks such as working with abstract data visualizations **(A)**, exploring volumetric data sets **(B)**, and making in-situ annotations **(C)**. All photos in this paper were shot with an externally tracked camera and do not fully reproduce the actual prototype.

Abstract

In this paper, we examine the potential of incorporating transparent, handheld devices into head-mounted Augmented Reality (AR). Additional mobile devices have long been successfully used in head-mounted AR, but they obscure the visual context and real world objects during interaction. Transparent tangible displays can address this problem, using either transparent OLED screens or rendering by the head-mounted display itself. However, so far, there is no systematic analysis of the use of such transparent tablets in combination with AR head-mounted displays (HMDs), with respect to their benefits and arising challenges. We address this gap by introducing a research platform based on a touch-enabled, transparent interaction panel, for which we present our custom hardware design and software stack in detail. Furthermore, we developed a series of interaction concepts for this platform and demonstrate them in the context of three use case scenarios: the exploration of 3D volumetric data, collaborative visual data analysis, and the control of smart home appliances. We validate the feasibility of our concepts with interactive prototypes that we used to elicit feedback from HCI experts. As a result, we contribute to a better understanding of how transparent tablets can be integrated into future AR environments.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Human-centered computing—Interaction design;

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1 Introduction

Many Augmented Reality (AR) systems use head-mounted displays (HMDs) together with additional, handheld mobile devices, such as phones or tablets (e.g., [7, 24, 53]). Research has shown that this combination can be advantageous [8, 43]. The mobile devices are used as tangible props or proxy objects to simplify manipulation (translation, rotation) of virtual 3D objects, as well as for their additional touch input. They also serve as personalized views, clipboards, and tangible magic lenses. In this way, complex AR use cases, such as Immersive Analytics [10], which demand a large repertoire of interactions [8, 12], can be supported. However, for many applications, occlusion by these additional input devices can be problematic: Both real world and virtual objects can be hidden, the visual context of the AR scene can be lost, and even in predominantly virtual scenes, the user's immersion may be broken when the mobile device is not combined with the 3D content in a realistic way.

A plausible solution to the occlusion problem is the use of transparent tangible displays. This includes both transparent display technology (e.g., using OLEDs) and transparent props with content rendered at their location by the HMD, effectively simulating a truly transparent display. On the other hand, such transparent devices have well-known problems arising from the inability to simultaneously focus on the transparent display and the scene behind it, affecting the precision of input and the perception of visual feedback [30].

So far, there is no systematic analysis of the use of transparent tangible displays for head-mounted Augmented Reality and its opportunities and challenges in augmenting real-world artifacts as well as virtual objects. With this paper, we address this gap.

We propose the concept of transparent tangible displays used with head-mounted Augmented Reality. We envision that these displays could serve both as additional input devices capable of touch and spatial device gestures and as personal views or magic lenses into the AR scene. By projecting 2D AR content onto the tablet's surface, these displays should furthermore facilitate rapid prototyping for transparent displays capable of in-situ output. We provide touch and spatial input techniques to interact with the unoccluded physical environment in combination with 3D AR visualisations and 2D tablet visualizations. We present interaction and visualization concepts for the aforementioned device combination. These concepts make use of the natural transparency of our envisioned devices, addressing the occlusion problems outlined above. We investigate the usefulness and remaining perceptional and interaction challenges of our concepts by addressing three use cases specifically: The exploration of 3D volume data, e.g., medical or biological data sets, the collaborative analysis of abstract data & data physicalizations, and the control of smart home applications such as smart light bulbs. Each of these application cases serves to highlight one or more of the core benefits of our concept: Our volume data use case demonstrates how transparent tangible displays can be used for spatial interaction with 3D data spaces without occluding the data or the physical context. The data analysis use case shows how transparent devices may reduce barriers between collaborators, allowing for more direct eye contact or picking up of facial cues. It also shows how physical artifacts can be annotated without occlusion. The smart home use case highlights how a transparent surface enables users to directly interact with physical objects from a distance and perceive changes instantly. These three use cases cover a wide range of combinations between physical and digital artefacts in different distances to the handheld device, from contact AR annotations on paper documents [18] to the distant control of smart devices.

We developed a research platform consisting of a custom-built, touch-enabled transparent interaction panel which supports capacitive multitouch and pen input, and accompanying software, which we make available to other researchers. With this contribution, we allow for rapid prototyping and facilitate future research into transparent handheld displays. We track this tangible controller in space with an infrared tracking system. As an HMD, we chose a Microsoft HoloLens 2, which we also use to show content on the transparent "display". Based on this platform, we present functional prototypes for the three use cases described above. They allow us to evaluate our concepts and to assess the impact of the interaction and visualization challenges mentioned above, by collecting feedback from experts and discussing the results of these hands-on sessions in detail. With this, we contribute to the future development of applications for transparent handheld displays.

In summary, the main contributions of this paper are:

- The *concept* of combining AR glasses with transparent handheld devices to introduce *interaction techniques* for sketching & annotation, data manipulation & exploration, as well as menus & UI tools using precise and hybrid input modalities.
- An easily replicable *research platform* consisting of a custom-built, spatially tracked *transparent handheld prototype* and an expandable open source software stack.
- Three implemented *use cases* that demonstrate how our approach can be used for exploring 3D volume data, to support collaborative data analysis, and to control IoT appliances.
- *Qualitative insights* into the opportunities and challenges of the use of transparent devices in AR, derived from five semi-structured *expert interviews* and *hands-on sessions*.

2 Related Work

Our work builds on prior research in the fields of mobile-assisted head-mounted AR and the investigation of transparent props and tangibles. In the following, we provide an overview of this related work and point out the key differences to our research.

2.1 Mobile Devices for AR

Following the idea of the personal interaction panel by Szalavári & Gervautz [45], mobile devices have previously been proposed for use as additional controllers in Augmented Reality. For example, Budhiraja et al. [7] looked into the combination of head-mounted displays (HMDs) with handheld displays to build what they call hybrid AR systems. Spatially-aware tablets for HMD AR have also been used for sketching [15], 3D modelling [34], to extend data visualizations (e.g., [24, 28]), or as general input devices for object manipulation and data space exploration (e.g., [8,29,37,53]). Sereno et al. [39] and Gosset et al. [16] use the multi-touch capabilities of mobile devices to support volumetric data visualization in AR. Similarly, Luo et al. [33] present work using spatial interaction with a tracked tablet to virtually slice through medical 3D data sets, while the AR headset shows a situated 3D model of the data. This is also related to research on tangible magic lenses, e.g., by Tsang et al. [46], Spindler et al. [40, 42], and Issartel et al. [25].

Our work draws on this prior work and our concepts make use of the same general interaction concepts, most prominently the window metaphor supported by spatially-aware tangible displays that allows to "directly" interact with objects seen through the device. However, opaque devices lead to occlusion of physical objects and co-located users. By leveraging transparency, we hope to address this limitation of the combination of AR with mobile devices.

Finally, the large field of mobile, video see-through AR is also related to our work. A full review of this research is beyond the scope of this paper. Some works particularly related to our use cases are sketching interfaces for AR, such as by Kasahara et al. [26], Suzuki et al. [44], and *Portalware* by Qian et al. [36], who combine a smartphone with a second display on a wearable.

However, while such systems address the occlusion problem of mobile devices, this typically leads to notably different perspectives compared to the view of the surrounding environment. A number of works explore user perspective rendering to address this. For example, Baričević et al. [3, 4] presented a prototype tablet using a Kinect and a Wiimote. A similar system was presented by Andersen et al. [2] who also used it for annotations in surgical contexts [1]. However, they do not support stereoscopy and the field of view is still limited to that of the small, handheld displays.

2.2 Transparency in Mixed Reality

Optical see-through AR HMDs see broad use in today's AR systems. However, in the scope of this paper, we only consider transparent displays that serve as additional, mobile or stationary screens, not the HMDs themselves. Such transparent displays have previously been suggested as a form factor for AR. For example, Hirakawa et al. [21] proposed a large, projector-based transparent screen as a means to digitally augmented physical environments and Hirakawa & Koike [20] extended this even for collaborative use. Similarly, Li et al. [31] also suggested a two-sided transparent display for collaborative use. On a smaller scale, AR smart windows see use in digital signage or exhibitions (see, e.g., [5, 23]).

Transparent props that reduce occlusion are also used in contexts similar to ours: The Gravity tablet prototype by Gravity Sketch Ltd[1] [13] is comparable to our work but solely focuses on sketching. The work by Schmalstieg et al. [38] on transparent props for the *Virtual Table* VR environment is also related to our work. They tracked a transparent sheet of acrylic glass over a back-projected stereoscopic display, simulating a transparent display for through-the-window interaction with virtual content. In contrast to their work, we utilize a multi-user capable Augmented Reality environment and also support multi-touch interaction.

Similarly, transparent props have also been used for tangible user interfaces, most prominently in the *metaDESK* by Ullmer & Ishii [47], which also introduces a passive "lens" tangible. This is closely related to the concept of Contact AR, presented by Hincapié-Ramos et al. [18, 19], in which a transparent tablet placed on printed documents is used to support active reading tasks such as annotations

[1] Gravity tablet: `https://vimeo.com/90951073`

or note taking. However, both approaches neither support 6 DoF interaction nor provide a stereoscopic view.

Our work touches on perceptional issues of transparency in AR. One of the most well-known challenges is the vergence-accommodation conflict [22], for which Kramida [27] proposes strategies to alleviate it in future HMDs. However, this is not unique to our concepts. A related challenge that is most apparent in systems using transparent displays is binocular parallax. This is an important depth cue but also leads to duplicated images (diplopia, [52]) if the transparent tablet and other real world objects are not at the same distance of the user. Valkov et al. [48] examined the resulting interaction problems and found that users typically touch between the two images of the target object with an offset towards the image for the dominant eye. Lee et al. [30] propose a technique called *Binocular cursor* to address this problem. Yoshimura & Ogawa [51] even make use of binocular parallax for interaction with large displays. While we do not aim to solve perceptional problems in this work, we examine the influence on various interaction techniques in our expert feedback sessions and, as a result, propose approaches to lessen the impact of binocular parallax.

3 Design Considerations for Transparent Tablets in Augmented Reality

We aim to explore the advantages and disadvantages of handheld transparent input surfaces in an AR context. With this, we try to help bridge the gap between real and virtual objects. In the following, we present our basic concept and further considerations concerning the design of a transparent tablet in AR.

3.1 Basic Concept

Our basic concept is that of a tablet-sized device with a transparent display, tracked in space, and used in combination with an Augmented Reality head-mounted display (AR HMD). Conceptually, such a display can be a transparent OLED or, as we implemented it in this project, a transparent device on the surface of which 2D AR content can be rendered. This approach allows us to not only explore the AR context, but also simulate a transparent OLED display.

Such a device can provide haptic feedback for precise interactions like sketching in AR and simultaneously serves as a tangible prop for intuitive mid-air spatial interaction. In contrast to currently used mobile devices in AR, the the transparency has several key benefits:

- Real-world objects are not occluded when interacting with them (e.g., for annotations), nor is their context.
- See-through touch screens allow precise touch & pen input in direct visual relation to both virtual and real objects.
- In co-located multi user scenarios, less occlusion means that the users can pick up more social cues (gestures, eye gazes, etc.), potentially benefiting their collaboration.

3.2 System Properties

The *technical capabilities* of the transparent surface include multi-touch sensing, enabling direct touch interaction as well as pen input. To ensure comfortable and efficient interaction, the fundamental *physical dimensions* of the transparent tablet need to be considered. For this project, its proportions were designed according to established digital tablets. Another relevant consideration is the *level of transparency* ranging from fully transparent to fully opaque. Permanently employing any level of opacity would impair the exploration of the potential of any higher degree of transparency. In contrast, a fully transparent display allows to simulate varying levels of opacity through virtual overlays. In the context of the AR environment, we recognize three main forms of *input*: 2D multi-touch input on the surface of the panel, the 3D pose of the panel, and the 3D pose of the HMD in relation to panel. Most of the possible interactions are facilitated through a combination of these parameters. A multitude of other input channels are conceivable, such as hand- and body gestures, voice, and eye gaze interaction. Though within this project, the main focus is on input that directly involves the transparent tablet. Since we mainly focus our exploration on the potential of the transparency, the *output* of this system is limited to visual AR content displayed by the HMD. It would also be possible to extend this by incorporating auditory signals or haptic feedback by the panel.

3.3 Interaction

The interactions users can perform range from 2D multi-touch or pen gestures on the transparent surface to 3D spatial interactions using the panel as a tangible prop. The mobility of the handheld device allows for movement in six degrees of freedom.
Besides conventional *multi-touch gestures*, there are several parameters to be considered when designing complex *spatial tablet gestures*, including the pose of tablet, the direction and speed of its movements, potential concurrent touch input on its surface (e.g., for dynamic 3D sketches or during clutching), and whether it is in direct contact with physical objects or planar surfaces. Furthermore, the direction of the users' head and eye gaze can be simultaneously considered to enable functionality akin to a magic lens, where physical and virtual objects can be observed and manipulated through a tangible window. For example, Boring et al. [6] employ a similar concept with touch interaction which is projected onto distant displays.

3.4 Context

The nature of Augmented Reality suggests a real world *environment* enhanced by spatially dependent virtual data. We suggest an indoor domain to fully take advantage of the systems capabilities and compensate for limitations such as poor visibility of AR content in bright daylight. Diverse application areas might benefit from such a setup, ranging from examples like data exploration in a professional research context to the control and enhancement of a private home environment. The spectrum of involved *data* includes purely physical objects, real objects with virtual enhancements, as well as purely virtual data. The placement of the virtual content in the real world environment is another relevant consideration when designing applications for a transparent tablet in AR. Virtual content can be placed independently, in relation to physical objects, or in relation to the tablet. Here, it can be shown as 2D (projected) content on the tablet or as 3D objects fixed in relation to it. The system can be used by a single *user* or in collaboration, depending on the scenario. A group of users might consist of one active operator and multiple passive observers, or multiple active users with transparent tablets.

4 Interaction / Visualization Concepts

In the following, we describe concepts for interaction and visualization techniques that can be realized by incorporating a *transparent* display in AR. We systematically investigate fundamental techniques based on three underlying main components: Using the display as an *AR prop or tangible* by tracking its movement and position in 3D space, employing it as an additional input device to allow for *on-tablet interaction* through touch gestures or pen input, and implementing a *tangible window metaphor*, where observations and interactions can seemingly be made through the transparent surface. The latter merges both of the preceding components by combining the panels position in relation to the environment (i.e., spatial interaction) with on-tablet interaction on the window pane. All of the following concepts incorporate at least one of the aforementioned core components and mostly depend on their combination.

4.1 Sketching & Annotation

Full body and hand gestures often lack the precision needed to perform delicate tasks. AR environments therefore often integrate additional input devices for precise interactions. The incorporation of a touch-enabled device allows for intuitive integration of pen &

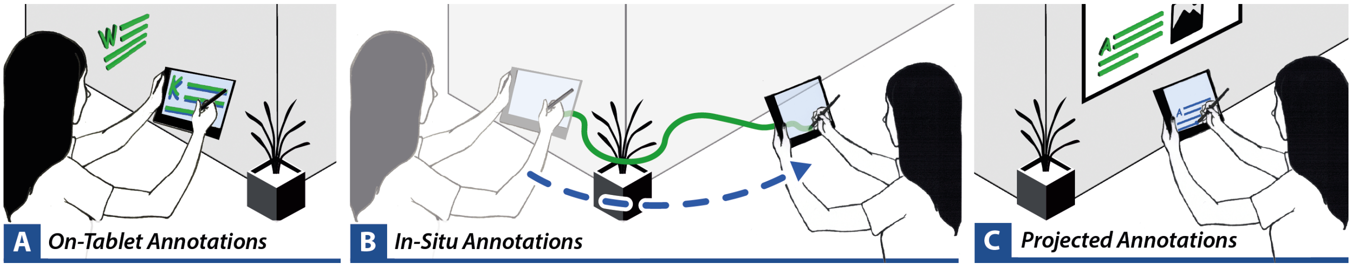

Figure 2: **Sketching & Annotation techniques** allow to seamlessly add user content in real-world contexts. We differentiate between *on-tablet annotations* **(A)**, *in-situ annotations* **(B)**, and *projected annotations* **(C)**. Holographic content shown in **green** and user interactions in **blue**.

touch input which can be used to sketch and annotate virtual content. Both of these tasks have been thoroughly researched and are prominently employed in many AR applications, such as mid-air object manipulation [49], rapid-prototyping of situated experiences [14,15], or the creation and sharing of interactive visualization for physics education, sports training, and in-situ tangible interfaces [44]. In the following, three techniques are proposed for creating annotations and sketches with a transparent touch-enabled surface in AR (see Fig. 2): On-tablet (A), in-situ (B) and projected annotations (C).

4.1.1 On-Tablet Annotations

The most obvious technique for sketching and annotating is derived from common pen & touch interactions with traditional digital tablets and consists of creating ordinary 2D strokes on the surface of the tablet. The resulting annotations or sketches can then be released into 3D space and later re-positioned as necessary. Effectively, this allows users to comfortably write annotations in a relaxed pose that can then be freely arranged in the environment to annotate both virtual or real content, e.g., to leave messages.

4.1.2 In-Situ Annotations

In-situ annotations are the result of free 3D sketching in space, using the tablet as a planar constraint. Users can directly annotate both virtual content and real objects, freely moving the tablet through space (see Fig. 1, C), e.g., to label specific parts of a volume visualization or to follow the surface curvature of a physical object. Here, the transparency allows them to always keep the context in view and precisely annotate even small features. Making use of the transparency of the device, in-situ annotations can also be made directly “on” physical objects by placing the tablet on a suitable surface, e.g., when directly annotating paper documents on a desk. A similar concept was presented by Hincapié-Ramos [18], using a semi-transparent LCD display placed on back-lit paper documents, and recently, Qian et al. [35] presented a smartphone-based AR annotation system.

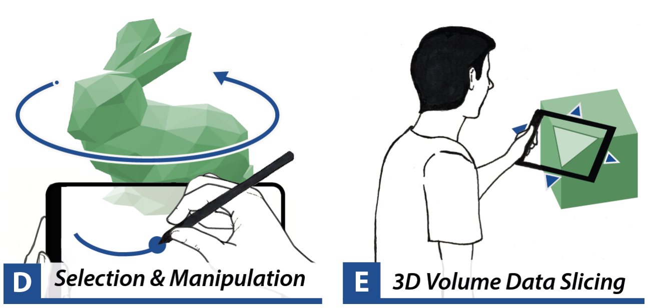

Figure 3: **Data Manipulation & Exploration** techniques allow to use the transparent tablet to transform (e.g., translate, rotate, or scale) virtual content **(D)** or to spatially slice 3D volume data **(E)**.

4.1.3 Projected Annotations

Making use of the tangible window metaphor, we propose the usage of projected annotations to remotely sketch on the surface of objects. Based on the device position and orientation, the location of the touch on the device and (optionally) the user’s point of view, the strokes drawn on the tablet are projected into the scene. For correct intersection of a touch’s ray cast with the scene, a model of the geometry is necessary. This is typically not a problem for virtual content and the depth mapping functionality of AR HMDs such as the HoloLens provides at least a coarse mesh of the environment. Projected annotations especially depend on the tablet’s transparency. They allow both interaction from a distance but also to directly sketch on arbitrarily shaped, e.g., irregular, surfaces.

4.2 Data Manipulation & Exploration

By combining the features of a tracked tangible prop with a transparent touch display, our envisioned device lends itself to various data manipulation & exploration tasks in augmented reality.

4.2.1 Object Selection & Manipulation

An advantage of transparency in our concept is that we can support various forms of object selection and manipulation while keeping the object itself and its context in view. This is important for real world objects which would otherwise be occluded, and may see use in applications for smart-home control, data physicalization, or situated analytics. However, even digital content rendered on or behind an opaque surface in AR, benefits from the unobstructed visibility of its real-world environmental context. Such touch-based *see-through manipulation* includes ray-cast based object selection by tapping on the tablet or by pointing a virtual cross hair, as well as rotation (see Fig. 3, D), translation, and scaling with touch gestures.

In addition, we propose spatial interaction with the device serving as a tangible prop. Similar to, e.g., [40], users can pick up virtual objects with the tablet, move and rotate the device to manipulate the coupled target hologram, and release the object again via touch.

4.2.2 Clipping

We propose different clipping techniques which facilitate the exploration of both volumetric data (see Fig. 3, E) and data visualizations suffering from occlusion, e.g., 3D scatter plots. For volumetric data, the device can not only be used to arbitrarily clip the volume but also to show a 2D slice with a different transfer function than the main volume visualization. Due to the transparency, the user can observe the volume during manipulation and no occlusion or indirection limits perception. For detailed inspection, the slice can be frozen or its position and orientation can be saved through a visual bookmark.

4.3 Menus & UI Tools

As our system additionally aims to serve as a rapid prototyping tool for transparent displays capable of in- and output, a surface-bound UI needs to take the observable real world background into account and support more complex interactions through strategically

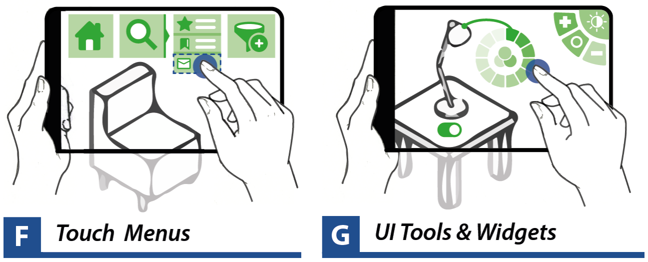

Figure 4: **Menus & UI Tools** enable precise and familiar gestural surface interactions, for instance, to browse *menus* **(F)**. Tablet-attached *UI tools & widgets* **(G)** provide versatile input capabilities.

placed *menus and tool palettes*. For example, in an immersive data visualization scenario, users may want to choose data sets and visualization types, specify filters, and configure views. Utilizing a conventional graphical UI, changes in the mixed reality environment can be instantly perceived live during interaction. For instance, a user changing the texture on a virtual object may immediately see how this object looks in its physical environment. Similarly, as our proposed device can serve as a transparent tangible window, real world artifacts (e.g., in a smart home setting) may be configured by pointing the device at them and using UI elements on the display (see Fig. 4), similar to some mobile AR systems, such as presented by Ye & Fu [50]. Any visual changes are immediately observable, minimizing attention switches.

In addition, the device can also serve as a *clipboard*. Digital content can be collected from the scene, stored for later use, or placed somewhere else. As the users are able to see both the content and the physical context during interaction, picking up digital artifacts can be easier and less error-prone.

5 Research Platform

To apply and evaluate our interaction and visualization concepts, we built a research platform to demonstrate how our approach can be conveniently used for real-world applications. In the following, we will present details on the overall setup and technical realization.

5.1 Setup & Technical Realization

Our technical setup comprises a custom-built transparent handheld tablet, a Microsoft HoloLens 2, an OptiTrack 3D tracking system, and a dedicated workstation for remote rendering.

Hardware Prototype. The handheld tablet prototype consists of a Raspberry Pi Zero 2 W, a 10" transparent capacitive multi-touch surface and a battery shield (see Fig. 5, A). To integrate all components into a wireless prototype in a space-saving way, all connection wires were cut to an appropriate length, equipped with small electrical connectors, and soldered onto the circuit boards. The capacitive touch controller is directly connected to the internal USB port of the Raspberry Pi and is natively supported as a HID compatible touch device by Raspberry Pi OS. In addition, the battery shield is attached to the power pins and incorporates a Li-po battery switching charger, 5V voltage boost chip, and a current sense circuit which enables battery status monitoring via I^2C. Overall, the 1000mAh battery lasts for about two hours and can be easily charged via micro-USB. Finally, all components are housed in a 3D-printed case which measures $29x19x1cm$ for a total weight of $330g$ (see Fig. 5, B). To ensure that the tracking system can precisely capture the tablet in space, we crafted IR reflective markers ($\varnothing 20mm$) and attached them to the tablet. They also serve as locking clips for the cover (see Fig. 5, C).

Prototype Software Stack. The tablet broadcasts touches in the local network over UDP. We capture these messages in our Unity client and inject them into Unity's touch event pipeline. The tracking data from the OptiTrack system is received via network using Natural Point's Unity plugin for NatNet[2]. The transformation between the OptiTrack and the Unity coordinate systems is computed based on a calibration process for which we use a set of three reference points. Each of these reference points consists of a printed QR code and adjacently attached IR markers. They are all registered in the tracking system as rigid bodies, with their local coordinate systems manually aligned to the QR marker. At the start of a session, we scan these QR codes with the HoloLens and compute the coordinate transformation between the corresponding sets of points. More reference points can be used for improved stability if necessary.

To allow researchers to build on our prototype, we release the source code under an open source license and provide detailed step-by-step instructions and resources as supplemental materials[3].

6 Implemented Use Cases

We propose three specific use cases to illustrate the applicability of our concepts based on the systematic investigation of interaction and visualization techniques in Sect. 4. In the first use case (UC1), the transparent input panel is envisioned as a tangible prop that aids exploration and annotation of medical volume data. In the second use case (UC2), it is utilized to facilitate immersive MR data analysis. The third one (UC3) uses the device as a control panel for AR-enriched smart home appliances. All described functions have been implemented for the final prototype, unless stated otherwise.

6.1 3D Volume Data Exploration

Medical volume data from Computer Tomography (CT) or Magnetic Resonance Imaging (MRI) is relevant for medical tasks such as pre-operative preparation, diagnostics, and for educational purposes. AR facilitates the intuitive, collaborative exploration of such data in 3D space. However, the manipulation and annotation of this data in AR might be tedious and awkward without additional input modalities.

Employing the transparent input panel as a *tangible prop* in this context can enable users to *arbitrarily clip* volume data by slicing into it (see Fig. 1, B). Meanwhile, the transparency of the device allows for an unobstructed view of the rest of the volume or any physical landmarks, as well as the collaborators hands. Furthermore, alternative representations of *individual slices* can be shown on the panel during clipping, offering additional insight into the data at the panels current position and orientation (see Fig. 6, B). Similar to Spindler & Dachselts annotation techniques for tangible magic lenses [41], these slices could then be directly annotated and saved as a collection of 2D images, however, this functionality has not been implemented within the prototype. Additionally, users are able to *freeze* the state of the clipping plane to inspect the data set independently from the panel's pose. If a specific view is deemed to be noteworthy, the panel's exact position and orientation in the volume can be *bookmarked* by tapping the display once. This creates a virtual panel emulating the tablets pose (see Fig. 6, D), which enables the expert to return to that exact position by aligning the physical panel with the virtual bookmark.

The user can *pick up* the volume by gliding the panel underneath it in a scooping motion (see Fig. 6, A). The visualization will stick to the panel's surface and can now be inspected by freely tilting and rotating the panel or re-located by detaching it at specific locations by tapping the panel once. If the orientation or scale of the data needs to be adapted from afar, e.g. in a collaborative scenario, the user targets the data by observing it through the transparent window and precisely *rotates or scales* through touch gestures on the surface.

The exploration of volume data often involves the identification and location of regions of interest, which can be *annotated* in order to highlight or comment on them, e.g., to direct the attention in

[2]Unity Plugin, NatNet: https://optitrack.com/software/unity/
[3]Project website: https://imld.de/clear-sight/

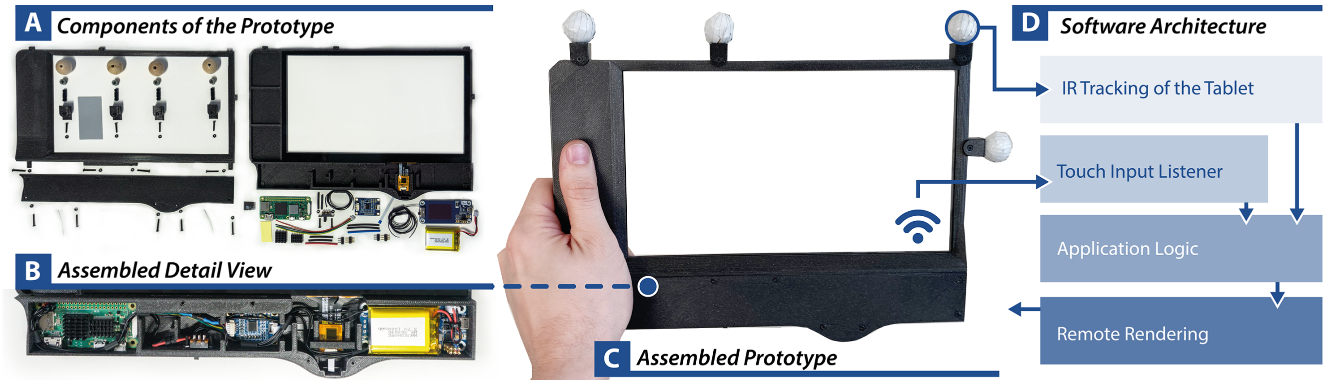

Figure 5: The **hardware prototype** basically consists of a Raspberry Pi Zero 2 W, a 10" transparent capacitive touch panel as well as a battery. All components are placed in a 3D-printed case with four attached reflective tracking markers. Our **software** provides the pose information of the tracked interaction panel and the touch events to the application. We use remote rendering to display holograms on the HMD.

collaborative scenarios. 2D *on-tablet annotations* might be suitable for longer strings of characters since they benefit from the advantage of a stable physical surface as a canvas. They can then be released into 3D space and manually placed at a desired position. *In-situ annotations*, however, might be more suitable for quick markings inside and outside of the volume (see Fig. 6, C). Specifically in an educational context, experts might also want to annotate physical objects, such as anatomical models. This may benefit strongly from the transparency of the panel, since the real object would usually be occluded and can now be observed during annotating and therefore facilitates precisely localized notes. Transfer functions play a notable role in the exploration of volumetric data and could also be manipulated via direct touch interaction on the panel. Although not yet implemented, we believe that the immediate visual feedback enabled by the transparency of the tablet would be beneficial.

6.2 Collaborative Analysis of Abstract Data and Data Physicalizations

In-depth data analysis often calls for diverse visualizations and collaboration, which we aim to support in this use case. Here, domain experts can work together while inspecting different 2D and 3D data representations, such as printed visualizations with virtual enhancements, purely virtual data representations, and data physicalizations [11] (see Fig. 7, A). The transparency of the panel allows for a free view of the physical, real-world context. It helps to keep collaborators in sight while allowing them to maintain eye contact and observe each other's lips and hands while talking, reducing the occlusion of social and contextual clues.

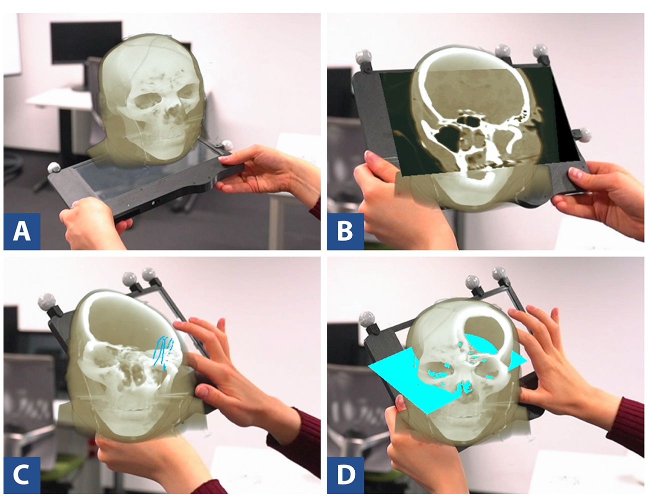

Figure 6: **Exploration of volumetric data**: Besides the clipping of a volume (see Fig. 1, B), a user can also pick it up for closer inspection **(A)**. Using the tablet as a tangible, arbitrary slices through the volume can be defined and viewed **(B)**. The volume can be frozen, allowing users to annotate directly on the clipped visualization **(C)**. Bookmarks can be created to indicate interesting slices **(D)**.

Using the panel as a *tangible prop*, users can *clip* 3D AR visualizations suffering from occlusion and crowding, such as bar charts and scatter plots (see Fig. 1, A). During clipping, users can *select* individual data objects on the panel's surface, which can then display additional information. The latter has yet to be implemented in the final prototype. The virtual models can be *manipulated* using interaction techniques already established in UC1, such as scaling and rotation through the transparent window, or picking them up with the tangible device to inspect or relocate them.

Our prototype already allows to *share selections* between *linked visualizations*. In the future, experts could dynamically create such logical links between different AR data models by drawing virtual connections. When observing physical data representations through the transparent window, the bounds of the panel act as a frame of interaction, enabling users to directly manipulate the data via touch gestures. A virtual overlay over the *physical data objects* allows for direct, visible feedback, e.g., highlighting selected bars on a physical 3D bar chart. These data physicalizations can also be precisely annotated using the *in-situ annotation* functionality, aided by an unoccluded view through the transparent surface. Additionally, users can directly create *projected annotations* on physical objects, e.g., hatching and shading of interesting areas. Projected annotations can be particularly useful in multi-user scenarios, because they enable collaborators to create large virtual sketches on physical whiteboards comfortably from afar, even while sitting. By employing multiple transparent displays, these annotations can be made true to the individual users' viewing perspectives, compared to annotating the camera output of conventional digital tablets. Virtual annotations can also be created on physical documents, as a way of non-permanently adding notes and sketches. The transparent surface offers high pen & touch precision compared to direct hand gestures for annotating. In a collaborative environment, the visibility of any virtual notes could be limited to one's personal view or shared among collaborators (see Fig. 7, C). The panel also allows for direct interaction with virtual enhancements and UI elements displayed on paper documents or the panel itself (see Fig. 7, B), e.g. tapping on an image under the screen to trigger the display of additional AR information. This concept has also been explored by [32], who use a digital pen instead. In future iterations of the prototype, more complex touch gestures could be employed as shortcuts for frequently needed functionality.

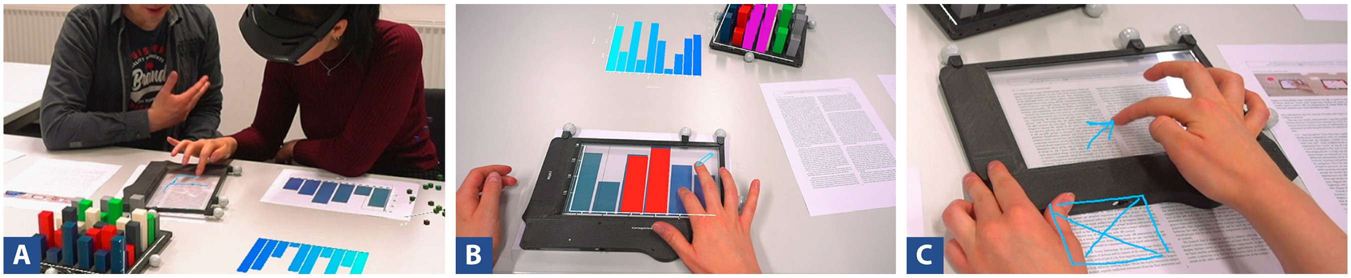

Figure 7: **Collaborative data analysis**: Our prototype demonstrates how transparent tablets can be used to support co-located multi-user data analysis **(A)**. Used as an overlay, the tablet allows selection in printed 2D and 3D charts. Corresponding data points in linked visualizations are highlighted **(B)**. Users can annotate documents by placing the tablet on top of them **(C)**.

6.3 Control of Smart Home Applications

Advancing technological developments have long arrived in private households and many people already live in smart homes. In this use case, the tablet functions as a *see-through control panel* for smart home appliances. The transparent window can act as a frame of reference to interact with these devices by observing them through it and *manipulating* them via touch gestures on the surface. The implemented scenario involves two smart appliances, a smart lamp[4] and a flower pot which senses the water level in its soil (simulated). Observing the flower pot through the transparent tablet reveals a virtual water level indicator. When the lamp is observed, a color wheel is displayed on the surface around it. The user can change the light color by dragging or tapping a finger along the wheel, while receiving direct, visual feedback (see Fig. 8, A). Possible future alterations include light intensity, patterns, and the incorporation of additional UI elements. Similar to [9], the user can *logically connect* both appliances' functionalities, by drawing a virtual line from the flower pot to the lamp on the surface of the tablet (see Fig. 8, B), resulting in a smart lamp that indicates the flower pot's water level by changing the color of the emitted light accordingly. Drawing connections between devices enables the implementation of simple logical conditions, akin to *rudimentary visual programming*. For future iterations, *off-screen visualization techniques* could be used to indicate the direction and position of different devices in a more crowded environment. Compared to 3D AR navigation aids, the tablet offers a flat frame of reference for these UI elements, reducing visual overload and avoiding difficulties with a limited FoV.

Additionally, the transparent tablet can be used to virtually annotate physical whiteboards and other household items through *projected annotations* (see Fig. 8, C). These notes could be limited to each resident's personal view or shared with others.

7 Expert Reviews

To validate our concepts, we conducted five review sessions with experts on Augmented Reality. Our experts (four male, one female) consisted of one postdoc with ten years of experience and four doctoral researchers with ten, four, and three years of experience in developing natural user interfaces. All of them have publications at relevant conferences, were recruited from our institute and did not receive compensation for their participation. Every interactive walkthrough session lasted approx. 90 min. (30 min. per use case). During the walkthrough, the experts were encouraged to think aloud and reflect on their experience. Afterwards, we structured our notes and categorized the experts' comments.

Transparency. Three out of five experts stressed the benefits of transparency in a context involving physical objects, two specifically liked the advantages of a less cluttered FoV. Three experts emphasized that during collaboration, the transparency helps *"recognizing the collaborators intention"* and *"getting a better sense of where other users are"*. Correspondingly, one expert found the transparency to be unnecessary when limiting the scene to a single user context with purely virtual objects. The experts also positively commented on using the panel as a transparent interactive window, describing it as *"natural"* and *"intuitive"*. One expert even noted that they kept looking through it during non-window interactions, another commented: *"I like to see the world through my little interaction frame."* However, one expert would have preferred conventional 2D UI elements over window interactions, to interact more indirectly and assume a more comfortable posture.

Perception. Only one expert expressed difficulties approximating the exact position of the tablet when it is occluded by the volume data set during clipping in UC1. Perception issues regarding accommodation to different focus planes were more frequent, specifically during UC3, when interacting with distant physical objects through the transparent window. Three experts reported exhaustion and difficulties in actively switching their focus from the distant object to the close panel, the remaining two described this effect as manageable, since *"the focus switch happens automatically."* Three experts noted that the binocular parallax also complicated precise selection on close physical objects through the transparent window. They all suggested continuous feedback as a solution, e.g. projecting a 2D representation of the selectable 3D objects onto the tablet or offering a pointer ray indicating the finger's position.

Interaction Concepts. The feedback regarding the purely tangible interaction was overwhelmingly positive among all experts. Three experts found it promising how virtual objects can be picked up and explored it by being fixed to the panel. Two suggested additional concurrent touch interaction to scale and rotate the object. All experts enjoyed using the panel to clip the volume data set in UC1, one specifically judging it to be *"a lot better than with free hand gestures."* Another expert recognized large potential in filtering data items by using the panel to clip the scatter plot in UC2. Three experts compared the feeling to interacting with magic lenses, specifically when the CT scan was attached to the panel in UC1.

All experts see an advantage in having a 2D plane for surface interactions on a stationary tablet and prefer it over free hand gestures, e.g. creating annotations and releasing them into 3D space. The concept of virtual annotations on real documents garnered mixed feedback: Two experts questioned its value and argued that the same interactions can be performed in AR without a tablet by using hand gestures. On the contrary, two other experts were particularly enthusiastic about this concept, one expressing interested in *"integrating this into complex applications, such as active reading and collecting literature."* The other specifically liked the idea of the tablet as an additional tool arguing that it *"reduces the complexity of interaction"* compared to AR gestures directly on paper, adding that the accuracy of the panel might enable precise touch gestures.

The most optimistic remarks were related to the interactions that combined the 3D pose of the tablet with the 2D input on the transparent surface, most notably the creation of in-situ and projected

[4] LIFX smart light bulb: `https://www.lifx.com/`

Figure 8: **Smart home control**: The transparent tablet allows to configure smart devices such as smart bulbs and directly see the effects, e.g., color changes **(A)**. By dragging from one device to another, connections can be created. Here, a (mock) humidity sensor in a flower pot is connected to a light **(B)**. Projected annotations allow users to directly annotate surfaces from a distance, e.g., to leave notes for relatives **(C)**.

annotations. All five experts see potential in these novel interaction techniques, one mentioning that they *"can imagine displaying UI control widgets on the tablet while annotating, as an advantage over free hand annotations"*. All five experts liked the in-situ annotations, stating that they felt intuitive and natural. Though two expressed that they found it difficult to create continuous 3D sketches, because approximating the distance between the transparent surface and a 3D stroke is challenging. Two experts see potential in projected annotations for being novel, easy, and convincing. Two others disagreed, with one arguing that they were too difficult to create.

8 Discussion

The strength of our concept manifests within complex use cases in multi-user environments incorporating both real and virtual objects. Such use cases for transparent tablets in AR had not been thoroughly investigated before, and we address this gap by utilizing our custom research platform. The feedback to our concepts was generally positive. While some issues were reported throughout the review sessions, most of the criticism was dependent on the individual and their preferences. Still, some open points of discussion remain.

Window Interaction. Besides the typical fatigue experienced during spatial interaction ("Gorilla arm" syndrome [17]), most of the criticism expressed during the expert feedback sessions revolved around the binocular parallax that leads to duplicated images when using the tablet as a transparent window. It was apparent that the severity of those issues strongly depends on the individual. However, even experts particularly affected by this still expressed an affinity towards the general concept window interaction and provided suggestions to minimize the amount of necessary focus switches. These propositions included projecting a 2D representation of the targeted 3D object onto the surface of the panel and casting a pointing ray from the fingertip, through the tablet and onto the targeted object. Related research also addresses this specific issue, proposing solutions such as Lee et al.'s concept of a binocular cursor [30]. With the development of our research platform we have implemented the technical foundation to not only explore the aforementioned propositions to solve common perceptional issues, but also create and investigate further solutions in a wide range of use cases.

Spatially Tracked Surface Input. During the feedback session, experts preferred interaction techniques involving a combination of 2D surface input with the panel's 3D pose, such as in-situ and projected annotations. They however also reported perceptional difficulties. The creation of continuous 3D in-situ sketches should be supported by an indication of the distance between virtual strokes and the transparent surface. Projected annotations are also impacted by binocular parallax. A possible solution could be to offer automatic or deliberate manual transitions from on-tablet to projected annotations, facilitating a smooth adaption of the user's focus point.

Collaboration. Throughout this exploration, we hypothesize that the transparency of the tablet supports collaboration through lessened occlusion of the collaborators faces and hands. Approving expert opinions gathered during the feedback sessions strengthen this idea. However, conducting a targeted quantitative study to investigate this claim was beyond the scope of this paper. Further research needs to be conducted to make a verifiable statement.

9 Conclusion

In this paper, we systematically explored the potential of incorporating transparent tablets into AR systems. We contribute the novel concept of combining these devices as well as a variety of interaction and visualization techniques that effectively utilize such tablets for interacting with real world objects as well as virtual content. We suggest several areas that may benefit from such a device, including virtual in-situ annotations on real objects, projected annotations from the user's perspective, and manipulating real and virtual objects through a transparent "window". We further see potential in transparency as a way to enhance collaboration and to avoid the occlusion problem. To technically validate our concepts, we constructed a research platform consisting of a custom-built handheld device with a transparent, touch-enabled surface and a corresponding software stack. With this contribution, we facilitate future exploration of transparent displays in AR. Our platform can also be utilized as a rapid prototyping tool for non-AR applications on transparent OLED displays. We further contribute three specific implemented use cases that demonstrate diverse usage scenarios for our approach: the exploration of 3D volumetric data, collaborative analysis of abstract data and data physicalizations, and the control of smart home appliances. We used them for interactive walkthroughs, which we conducted with domain experts to gather feedback and further validate our concepts. The observations from these review sessions enabled us to reflect on common challenges derived from the usage of transparent tablets in AR. With these insights, we contribute to the future development of applications for transparent handheld displays. They will also inform future technical improvements, refined interaction & visualization concepts, and extended use cases to be evaluated in formal studies. Our concepts and open source prototype demonstrate the potential of interacting with transparent tablets in AR and outline how future AR systems may benefit from this novel approach.

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