Reverse Vampire UI: Reflecting on AR Interaction with Smart Mirrors

Sebastian Rigling
University of Stuttgart
Stuttgart, Germany
sebastian.rigling@visus.uni-stuttgart.de

Ševal Avdic
University of Stuttgart
Stuttgart, Germany
st155243@stud.uni-stuttgart.de

Muhammed Enes Özver
University of Stuttgart
Stuttgart, Germany
st154965@stud.uni-stuttgart.de

Michael Sedlmair
University of Stuttgart
Stuttgart, Germany
michael.sedlmair@visus.uni-stuttgart.de

Figure 1: Our AR smart mirror prototype shows a UI in the mirror space. The reflection of the user touches it from "behind."

Abstract

Mirror surfaces can be used as information displays in smart homes and even for augmented reality (AR). The big advantage is the seamless integration of the visual output into the user's natural environment. However, user input poses a challenge. On the one hand, touch input would make the mirror dirty. On the other hand, mid-air gestures have proven to be less accurate, slower and more error-prone. We propose the use of an AR user interface (UI): Interactive UI elements are visible "on the other side of the mirror" and can be pressed by the user's reflection. We built a functional prototype and investigated whether this is a viable option for interacting with mirrors. In a pilot study, we compared the interaction with UI elements placed on three different planes relative to the mirror surface: Behind the mirror (reflection), on the mirror (touch) and in front of the mirror (hologram).

CCS Concepts

• **Human-centered computing → Mixed / augmented reality**; **Interaction techniques**; *Touch screens*; Gestural input.

Keywords

augmented reality, mirror, interaction

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1 Introduction

There is a lot of research on augmented reality (AR) mirrors [17] and smart mirrors connected to Internet of Things (IoT) systems [1]. A display placed behind a half-silvered mirror (two-way mirror) can be hidden from plain view. In this way, it can be seamlessly integrated into the user's natural environment. After all, mirrors are objects that can be found in every building and household. Therefore, they offer immense untapped potential for the use in ambient and ubiquitous computing [9].

A quick online search shows that the vast majority of commercial interactive mirrors rely on capacitive touch sensors for user input. Only a few products offer mid-air gesture recognition or alternatives such as voice control or the connection to a mobile app. One of the reasons for this is the obvious user-friendliness and unambiguousness of the touch user interface (UI): The functions are mapped to labeled buttons that make the interaction very clear to the user. When one of them is pressed, the user's intention is very clear to the system. On the other side, the user receives immediate (haptic) feedback. The disadvantage of touch is that it leaves fingerprints on the mirror surface.

Mid-air gestures avoid contact with the mirror surface. However, there are no universal gestures and functions, which means that every system requires prior knowledge or training [25]. On the technical side, the interpretation of gestures and user intentions leaves more room for error. Jakobsen et al. [11] compared mid-air gestures and touch input for selection tasks on large displays. Their results show that touch is more precise, faster, and less error-prone than mid-air gestures. And that when given the choice and all targets are within reach, users will choose touch over gestures.

We propose a system that offers a novel input modality which is unique to AR mirrors. Our system is based on the interaction of the user's reflection with an immersive AR UI in the mirror image. We believe that it can combine advantages of both, a touch UI and mid-air gestures. In short: The user presses mid-air AR buttons which provide the same user-friendliness and unambiguousness as touch buttons, just without the haptic feedback. It is therefore similar to "holographic" mid-air AR buttons displayed on a head-mounted display (HMD), but the interaction is performed by the user's reflection in the mirror. The main difference is the depth perception and that the user does not have to wear an HMD.

When there is a gap between the display and the half-silvered mirror, the displayed UI appears to be "in the mirror". It does neither require a stereoscopic display and head tracking, nor does it suffer from the vergence-accomodation conflict like other AR systems [14]. The user can perceive both the UI and the reflection at the same depth without either appearing blurred. The simplicity of the setup required to create immersion and presence is unique to reflective AR mirrors. As the UI is only visible in the mirror image, it can be thought of as an "inverted vampire" (who in contrast—according to folklore—are visible to the naked eye, but *not* in the mirror image).

To our best knowledge, there has not yet been research in this direction of "AR smart mirrors" including a comparison of this novel input modality with touch and holographic (HMD-based) AR. In our pilot study, preliminary results suggest that the proposed AR interaction can indeed perform similar to touch input in this setting. The main contribution of our work is the design and implementation of a functional prototype and the results of a comparative pilot study with considerations for future work.

2 Background and Related Work

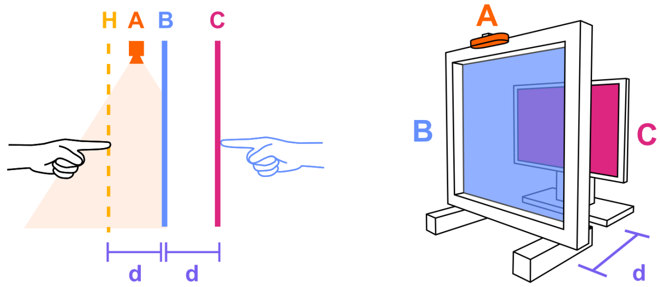
AR mirrors have been investigated for improving the shopping experience of make-up [12] and fashion [3, 21, 26], remote collaboration [10], anatomical learning [4, 5], health awareness [2, 20], motion guidance [23, 28, 29], and many other use cases. They are also known as *mirror-based AR* [13], *mixed reality mirrors* [22, 29], *(augmented) virtual mirrors* [8, 16], or *magic mirrors* [19]. On the one hand, there are camera-based AR mirrors [19], which are often used in research. This is a normal display that shows a flipped live video from a camera. The camera is directed away from the screen towards the area in front of it. The displayed image is 2D and the camera perspective is static. In this respect, it is very different from an optical mirror, but does allow for more control over image composition. On the other hand, there are reflective AR mirrors like we described above: AR content is displayed on a screen behind a half-silvered mirror [22]. These systems display virtual objects on a 2D display *directly* behind the mirror [13, 30], on a stereoscopic 3D display *seemingly* closer or further away [15], or on a 2D display *at a physical distance* behind the mirror [24]. In the style of the latter, we want to create a 2D UI parallel to the vertical surface of the mirror. The UI is supposed to look like it is part of its reflection. Users interact with it through the reflection of their fingers.

Martinez et al.[18] developed a system that uses this exact input modality: Museum visitors can see both the reflections of their hands in front of and the *physical* objects behind the glass of the display case. The reflections act as the visitors' avatars, allowing them to select exhibits and press 2D buttons that are projected onto the horizontal surface next to the exhibits. We want to explore the same idea of a "reflected avatar," in our case for a virtual UI.

In their detailed overview on the topic of AR mirrors, Martin-Gomez et al. [17] concluded that humans indeed interact naturally with AR mirrors based on their natural experience with mirrored views. Even complex tasks (such as surgery) would only require a little practice. To find out whether our modality is actually useful for the intended use in smart mirrors, we want to compare it with other modalities. There are two similar comparisons in related research:

Weiss et al [27] performed a Fitts' law test comparing holographic AR on a HMD with a regular touch screen display. The results show that the touch screen modality performed better in all aspects (accuracy, precision, error rates, throughput, and movement time). They attributed this to the complexity of mid-air selection in AR and the lack of haptic feedback, but also to technical limitations of the used *Microsoft HoloLens 2*.

Karg et al. [13] compared AR instructions for a manual assembly task on an AR HMD and a reflective AR mirror. Their results show that the HMD was clearly superior. One reason for this could be that the AR mirror used a flat 2D display compared to the stereoscopic display of the HMD. The discrepancy in depth perception and the mismatch between the vertical 2D visualization plane of the AR instructions and the horizontal 3D interaction plane of the physical assembly task may have affected the results of the AR mirror. For our design, we want to take these aspects into consideration.



(a) Side View (b) Physical Components

Figure 2: An overview of the prototype. The schematic side view (a) shows the Leap Motion controller *A*, which tracks the user's hand in front of the half-silvered mirror *B*. The display *C* is located at a distance *d* behind the mirror. The user inputs are registered on the interaction plane *H* at which the hand's reflection appears to "touch" the display from behind. The drawing (b) shows the components in the physical prototype.

(a) Hologram (b) Touch (c) Reflection

Figure 3: The three locations of the UI: Hologram in front of the mirror surface (a), Touch on the mirror surface (b), and Reflection behind the mirror surface (c).

3 Prototype

The setup of our proposed system is very simple. Fig. 2a shows a schematic representation of our design from the side view. We built a wooden frame to hold a 600×600×4 mm half-silvered mirror with 8% light transmission (Fig. 2b). The UI is displayed on a LCD monitor, which is located at a distance *d* behind the mirror. The area behind the mirror is dark, so that only the UI on the display is visible through it. We have installed a lamp to ensure that the user's hands are well lit and clearly visible in the reflection. A photo of the finished prototype with d = 10 cm can be seen in Fig. 1.

For hand tracking, we used a *Leap Motion Controller 2*. In initial tests, we found that the tracking was more robust from the top than from the bottom. Therefore, we placed the camera on top of the wooden frame facing downwards to track the user's hands in front of the mirror. To increase the contrast in the infrared camera image, we used matte black for the wooden frame and tabletop.

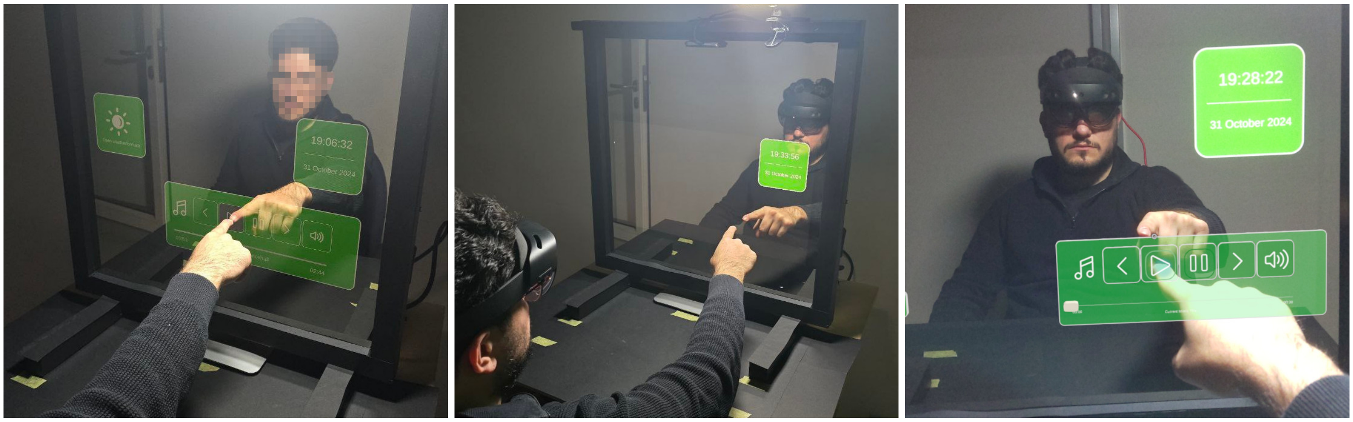
Our software uses the *Unity*[1] game engine to process the hand tracking data and render the UI. In it, we defined a 2D interaction plane parallel to the mirror and the display. When the position of the index finger tip passes through this plane, it is registered as user input (e.g., *press* or *drag*). We implemented an interactive smart mirror UI with time, date, a button to display weather information, and buttons and sliders to control a music player. As additional feedback to increase presence, we display a dark circle in the area where the finger passes through the interaction plane: It looks as if the reflection is penetrating the UI from behind.

If in the software, we set the 2D interaction plane in front of the mirror so that it is at the same distance *d* from the mirror as the display behind it, the reflection of the fingertip will be at the same distance as the UI. A distance of approximately d = 0 cm results in the interaction plane coinciding with the UI, so that the mirror becomes effectively a touch screen.

4 Pilot Study

We wanted to compare three modalities as illustrated in Fig. 3: a) Hologram, a holographic UI in front of the mirror, b) Touch, the mirror is used like a regular touch screen, and c) Reflection, the use of the hand's reflection for interacting with the UI in the mirror space. We configured our prototype for each input modality: We set the interaction plane to d = 10 cm for the Reflection (Fig. 1) and d = 0 cm for the Touch (Fig. 4a) modality. For Hologram, we built a second software that runs on a *Microsoft HoloLens 2* AR HMD (Fig. 4b). The holographic UI (Fig. 4c) looks identical to the smart mirror UI and is located in the same position as the

[1] https://unity.com/



(a) Touch interaction **(b) HMD (third person view)** **(c) HMD (first person view)**

Figure 4: The additional configurations of our prototype for the pilot study: For touch interaction (a) and for the HMD (b) with holohraphic UI elements (c).

interaction plane at $d = 10$ cm. This ensures consistent interaction across all three modalities.

We recruited 12 paid participants (5F/7M, age 22–28, marked as P1–P12) via convenience sampling. Our study followed a within-subject design in which we asked the participants to interact with our prototype. There was one condition for each modality.

For a condition, the system was calibrated to the participant and instructions were given on how to use the current modality. Afterwards, we asked the participant to follow the instructions and interact with the UI to: play and pause music, change tracks, move forward and backward on the song slider, change the volume, and call up weather information. When they had completed these tasks, they were given some time to explore the modality for themselves. While they did, we asked them to think aloud and asked follow-up questions to get more insight into their user experiences. We took notes on what they said. Then we asked them to fill out the NASA-TLX form and answer five additional questions on the Likert scale, where 1 meant "strongly disagree" and 5 meant "strongly agree":

Q1) The input method was pleasant.
Q2) The inputs were recognized correctly.
Q3) I would prefer the input method in the long term.
Q4) Interaction with the buttons was easy and pleasant.
Q5) The interaction with the sliders was easy and pleasant.

For every participant, we repeated this procedure for all three conditions. We counterbalanced the conditions over all participants using a balanced Latin square. After the participants completed all conditions, we collected their general feedback. We wanted them to imagine a scenario that had an "ideal" system: This could mean that there might be a touch-enabled smart mirror that would *not* show finger prints. We asked the question on the same Likert scale:

Q6) Would you use the AR mirror in your daily life?

In follow-up, we asked open questions about how they would improve the current system. Ultimately, in a post-study questionnaire, participant information was collected on gender, age, and previous experience with AR and smart mirrors.

5 Results

Below we summarize quantitative results and qualitative feedback from our pilot study. We follow what we consider to be current best practice in human–computer interaction research [6, 7] and report the results with 95% confidence intervals (95% CI).

5.1 Quantitative Feedback

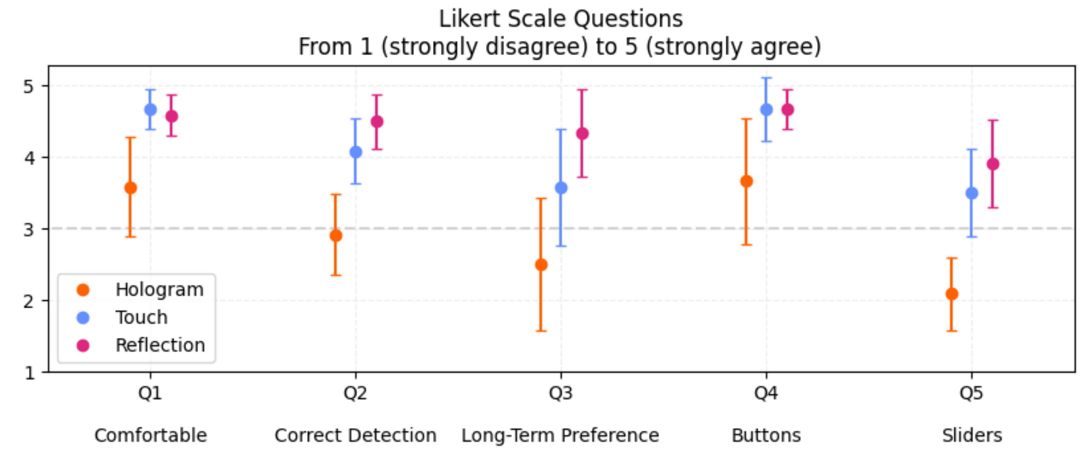
All participants stated that they already had prior experience of using a touchscreen. Apart from one participant (P8), no other participant had experience interacting with a smart mirror. Whereas 4 out of 12 participants stated that they had some previous experience with holographic interaction.

A visual analysis of the three modalities shows that Touch and Reflection are very similar for both our usability-related questions (Fig. 5a) and task load (Fig. 5b). The participants' long-term preference tends to be for Reflection, while the mental load for Touch is generally lower. In relation to questions Q1–Q5, Hologram was generally perceived worse than both Touch and Mirror. For task load, Hologram stands out for effort and frustration, scoring the highest. It also tends to require more mental and potentially more physical demand than Reflection.

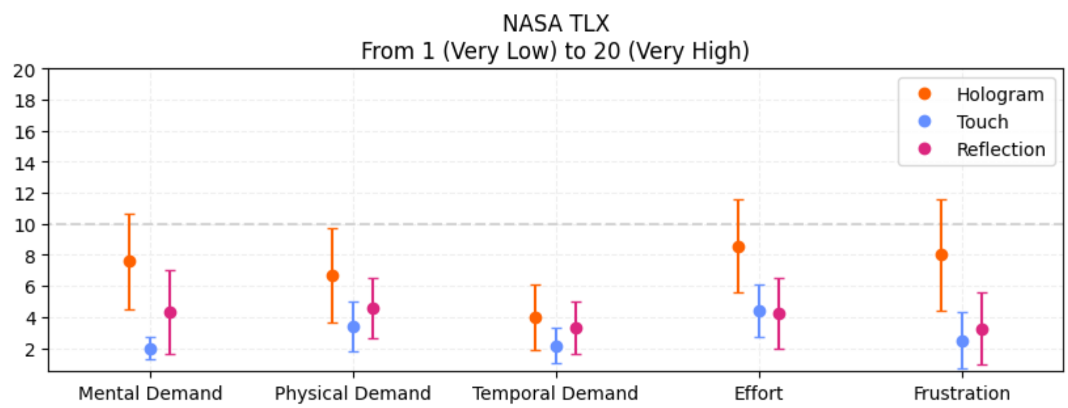
5.2 Qualitative Feedback

Most participants (10 out of 12) stated that they preferred a clean mirror surface, even though touch interaction was perceived as more natural. Only two participants stated that they would still prefer Touch over the other two modalities. One of the participants (P8) owns a touch-enabled smart mirror at home. She shared her experience that the mirror often recognizes incorrect user input during cleaning. The frustration was even greater because the fingerprints from the touch input meant that cleaning the surface (and therefore incorrectly recognized input) was required more frequently.

Half of the participants (6 out of 12) stated that they were aware of their reflection when using the mirror interaction. Six participants using Hologram and three participants using Touch found



(a) Comparison of the usability-related questions (Q1–Q5) on the Likert scale for all three input modalities: Touch and Reflection are similar, with a leaning towards Touch in Q3 (long-term preference). Hologram generally has lower scores.



(b) Comparison of the NASA-TLX for all three input modalities: Touch and Reflection perform very similarly, with the exception of mental demand, where Touch is much better. Hologram tends to require more mental demand and potentially physical demand. It stands out in regards to effort and frustration.

Figure 5: Results of the comparative pilot study for the questions Q1–Q5 (a) and NASA TLX (b). Errorbars show 95% CI.

that the UI distracted their focus from the reflection. One participant stated that they did not like having to pay close attention to their reflection when using the mirror interaction. Five out of twelve participants stated that they liked that Reflection and Hologram required less physical effort as the distance to the UI elements was shorter.

Two thirds of the participants (8 out of 12) found the visual feedback in the mirror interaction to be useful. About half (5 out of 12) assumed that the modality was effective with a little practice. Using the *Microsoft HoloLens 2* for Hologram interaction caused frustration among the participants: The main reasons given were difficulties in operating the sliders (6 out of 12), difficulties in determining the distance to the UI elements (2 out of 12) and the feeling of a slow response time (2 out of 12). However, eight out of twelve participants could imagine preferring Hologram over the other modalities "in an ideal world". This would mean that a) hand tracking would be faster and more reliable and b) the technology could be integrated into the mirror.

6 Discussion

Touch input seems not ideal for mirrors. The participants wanted to keep their mirrors at home clean and free of fingerprints. This was the main reason why almost all of them would choose an input modality other than Touch if they had smart mirrors at home. One participant, who had a touch-enabled smart mirror at home, backed up this claim with her own experience. Especially because she frequently experiences wrong inputs during cleaning the mirror surface, which could also be avoided if the surface and interaction plane were not the same.

Lazy interaction is good. Participants mentioned that they liked that with Reflection and Hologram they did not have to stretch their arms as far as they would have to if they wanted to touch the mirror. This is in line with the research by Jakobsen et al. [11]. Unlike many mid-air gestures, which are only robust with sweeping movements, AR buttons can be limited to smaller areas that are convenient and easy to reach.

In an ideal world, we would have holographic buttons. Even though Hologram performed considerably worse than Touch and Reflection, most participants would prefer the holographic buttons in front of the mirror. The reason for this is that this modality theoretically has the same advantages as Reflection, but is more similar to regular touch input—and therefore easier to use. One explanation for the bad scores is in the choice of the *Microsoft HoloLens 2* for the comparison. The participants were not used to handling the device, which could be the reason why many of them reported problems interacting with the holographic UI. The difficulties encountered were also similar to the observations made by Weiss et al. [27]: Participants reported that input was slow and that they had difficulties with depth perception. One additional factor might have been that our Hologram UI lacked a cut out of the user's hand to simulate occlusion. Repeated attempts to use the UI, holding up the hand, and discomfort of wearing the device may have influenced effort and frustration values. However, the AR HMD was only the means to an end, because we could not use "real" holographic buttons for our comparison. For future studies, we propose using consistent display and tracking technology across modalities for better comparability of the results.

In a less ideal world, we should reflect on mirrors. One reason why in the evaluation Reflection scored better than Hologram could be its technical feasibility. Our prototype is easier to implement in a real-life scenario compared to holographic AR buttons that actually float in front of the mirror. The latter sounds more like science fiction, while our prototype is a proof of concept of the former. The technology used is simple and readily available.

As easy as reflections. In the evaluation, Reflection was almost equivalent to Touch and only required more mental effort. This is not surprising, as touch interaction is an extremely familiar concept, while using one's own reflection for AR interaction is not. As the participants pointed out, practice could provide a remedy to this problem. They also noted that this modality does not distract their attention from their own reflection, which is what they normally focus on when using a mirror. This is an indication that users could actually avoid context switching when interacting with a smart mirror.

7 Limitations and Future Work

The main focus of our work was building a functional AR smart mirror prototype as a proof of concept for interactive reflection. The pilot study was not designed to derive generalizable conclusions from the results. We wanted to gain a better understanding of the user experience and general feedback, which could then be used for a more comprehensive study design. We share our results, because we believe that they contribute to the discussion on the topic and design considerations of future work.

The main drawback of our prototype was that for a comparison, we had to simulate holographic AR buttons in front of the mirror using the *Microsoft HoloLens 2*. The inconsistency between display and tracking technologies among modalities limited the comparability of the results, as described above. In future work, another prototype should be used that can display the UI for all three modalities with technological consistency. This could mean that either an AR HMD or a stereoscopic 3D display is used to display the UI on all three planes (in front of, in, and behind the mirror surface). However, a prototype developed specifically for this comparison will differ from any target system and thus come with its own drawbacks.

8 Conclusion

We asked ourselves what the best input modality for smart mirrors could be. To this end, we wanted to find out whether interaction with AR UI elements in the mirror using the reflection of the hand is comparable to normal touch and AR input. We built a smart mirror prototype, conducted a pilot study, and discussed the results of the comparison of the three input modalities. Even if at first the interaction required more mental effort than touch input, it offers advantages compared to other smart mirror input modalities. Research in this direction is only at the beginning, but shows great potential.

Acknowledgments

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