Reflected Reality: Augmented Reality through the Mirror

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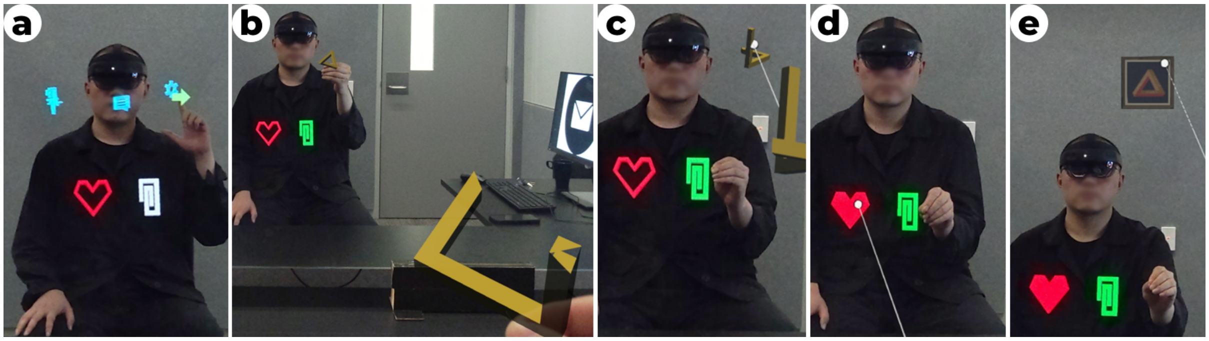

Fig. 1. Example interactions in *Reflected Reality* afforded by the combination of a smart mirror and a HoloLens 2 (captures of mirror reflection by the HoloLens 2). The virtual objects on the user's reflected body and around the head are rendered on the smart mirror, while the other objects are rendered through the AR headset. *a*: User can interact with objects rendered on the smart mirror using the reflected body as an avatar; *b*: User can see and interact with objects and their reflections rendered through the headset, using their physical hand and their reflected hand; *c*: User can remotely interact with objects in the reflection by raycasting through the mirror; *d*: User can remotely interact with body-attached objects rendered on the smart mirror; *e*: User can remotely transport objects rendered through the headset from the physical space into the mirror space.

We propose Reflected Reality: a new dimension for augmented reality that expands the augmented physical space into mirror reflections. By synchronously tracking the physical space in front of the mirror and the reflection behind it using an AR headset and an optional smart mirror component, reflected reality enables novel AR interactions that allow users to use their physical and reflected bodies to find and interact with virtual objects. We propose a design space for AR interaction with mirror reflections, and instantiate it using a prototype system featuring a HoloLens 2 and a smart mirror. We explore the design space along the following dimensions: the user's perspective of input, the spatial frame of reference, and the direction of the mirror space relative to the physical space. Using our prototype, we visualise a use case scenario that traverses the design space to demonstrate its interaction affordances in a practical context. To understand how users perceive the intuitiveness and ease of reflected reality interaction, we conducted an exploratory and a formal user evaluation studies to characterise user performance of AR interaction tasks in reflected reality. We discuss the unique interaction affordances that reflected reality offers, and outline possibilities of its future applications.

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CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; **Interaction techniques**; **HCI theory, concepts and models**.

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1 INTRODUCTION

> *"Now, if you'll only attend, Kitty, and not talk so much, I'll tell you all my ideas about Looking-glass House. First, there's the room you can see through the glass—that's just the same as our drawing room, only the things go the other way."*
>
> — Lewis Carroll [8]

Alice's fantastical adventures through the looking-glass started with an ordinary observation: the mirror reflection of a room appears as another room in the opposite direction. Intuitively, this impression is shared by children at their first glance of a mirror, and even by entire cultures that believed in its "absorbing" nature [22, 43]. Today, the pervasiveness of the mirror as a domestic object conceals the "everyday magic" [43] that provoked the intriguing fantasies by Lewis Carroll. If we were to take a closer look at this overlooked "magic" and try to simulate it using "modern-day magic"—namely computer graphics and interactive technologies—we can see the mirror as a display of a virtual space behind its surface with high visual resolution and real-time tracking and playback of real world events in 3D—the very same characteristics that define Augmented Reality (AR) [3]. In this paper, we aim to bring this "magic" to life by presenting a novel design space for AR interaction with mirrors, and by empirically investigating its usability.

But how can we reach the reflected space through the hard surface of the mirror? The past few years have seen a series of works that explored the use of two-way mirrors for providing realistic visual AR experiences [24, 33]. For instance, Plasencia et al. contributed a design space for AR mirror displays, and briefly discussed the possibilities and limitations of such systems [33], while Jacobs et al. explored the use of the augmented mirror space for artistic performances [24]. Whereas previous works offered inspiration for using mirrors as novel displays, the rich interactivity provided by AR Head-mounted Display (HMD) have not yet been explored for interacting with mirror reflections. In this work, we extend the smart two-way mirror literature with the addition of an AR HMD, which augments both spaces across the mirror, expanding the interaction affordances of AR into a new dimension of mirror reflections.

Unlike existing mirror-based AR interfaces, the addition of an HMD combining with the smart mirror, with its abundance of interaction modalities, grants us the conceptual power to re-imagine the reflected space behind the mirror as a full-scale malleable AR space, and to redefine the relationship between the user, their surroundings, and their reflections in AR. Following a summary of related work, we unfold our design space of ***Reflected Reality*** by exploring its three dimensions: user's *first-person* (1PP) or *second-person* (2PP) Perspective of input using their real or reflected body; *egocentric* and *allocentric* Frame of Reference for defining the spatial relationships between objects and bodies in the physical space and in the mirror reflection; and the Direction of the mirror space used as a *reflection* or *extension* of the physical space in different interaction contexts. To instantiate this design space, we implement a proof-of-concept prototype system consisting of a smart mirror and a HoloLens 2. Using the prototype, we visualise a use case scenario that covers the main types of novel interactions derived from our design space. To understand how users perceive the example interactions demonstrated in the use case scenario, we conducted an exploratory evaluation by guiding participants through the scenario. After identifying characteristics of reflected reality interaction commonly mentioned in the feedback from the exploratory study, we subsequently conducted a formal evaluation to quantitatively characterise user performance and the perceived difficulty of basic AR target selection and visual search tasks in the mirror, while providing a better understanding of the usability of reflected reality interaction and its strengths and limitations. We discuss the unique interaction affordances provided by this design space in light of user feedback and performance results in the two evaluation studies. Finally, we propose future applications and discuss reflected reality's implications for future work on augmented mirrors and on AR interaction at large.

2 RELATED WORK

In this section, we take stock of mirror-based interfaces in the HCI literature and categorise them by how they use the reflection. We chart the evolution of augmented mirror interfaces from simply rendering 2D information on the user's reflection towards blending 3D AR content with the reflected space. We discuss the literature on human perception of mirror reflections, and the opportunities for leveraging the reflected space for novel AR interactions.

2.1 2D augmented mirror displays

Because mirrors are pervasive in domestic and public spaces, there has been a continuing interest for turning them into ambient displays while borrowing from interaction techniques and metaphors found in public displays [32]. For instance, *AwareMirror* is a personalised ambient display for information such as time and weather, incorporated into its users' daily routine [15, 16]. The prototype used a two-way mirror overlaid on top of a monitor, which is a common way to blend the display content with the reflection. Similar works have extended this and attempted to incorporate novel input modalities and use cases, such as voice commands and emotion recognition [2, 11].

By placing mirrors at different angles in the 3D space, previous works explored alternative ways for users to perceive their bodies. For instance, learners of motor tasks can benefit from observing reflections, to obtain visual knowledge of the task from an alternative perspective [4], and to see visual movement instructions overlaid on their bodies while attempting to replicate the movement [1]. Whereas these works showed example use cases of augmented mirror interfaces, they have not attempted to augment mirror reflections in 3D with understanding of the reflected spaces.

2.2 Mirror Displays for AR in the 3D space

Another line of research attempted to build AR interfaces based on mirror reflections (for a review, see Portalés et al. [41]). Compared with 2D augmented mirrors, these works aimed to blend the virtual augmentations rendered on the mirror display with the reflection in the 3D space. Sato et al. presented an *MR-Mirror* prototype that featured a two-way mirror on a body-sized monitor, and calibrated its display to the viewing perspective of the user [46]. More mirror-based AR interfaces followed the release of the Microsoft Kinect sensor, such as Microsoft's own *Holoflector*[1]. These prototypes benefited from the Kinect's depth sensing and body tracking capabilities for easier implementation of view-dependent rendering and bodily interactions. Jang et al. presented a calibration method for mirror-based AR displays with a similar setup [26], and implemented depth-of-field matching to explore its effect on users' perception of the virtual objects displayed on the mirror [25].

Fewer works have explored the possibilities of interaction with such interfaces, most of which were presented in novel contexts such as "entertainment, edutainment, clothing, arts, and medical therapy" [41]. Examples of such use cases include playing a virtual drum set behind the mirror using body reflections [30], and controlling the position of virtual augmentations through body tracking [20]. Jacobs et al. presented *The Performative Mirror Space*, for which they explored the potential of using augmented mirrors while involving the use of physical context and narrative [24].

Other works have expanded the use cases of mirrors in AR with more complex hardware. Most notably in *Through the Combining Glass*, Plasencia et al. explored different spatial arrangements of the mirror and the monitor, to enable interaction happening in the gap between them, where real and virtual objects were blended to induce a more convincing depth illusion [33]. Other related works used two-way mirrors for 3D hologram interactions without the mirror metaphor. With *HoloDesk*, users could manipulate virtual objects by reaching into an interactive

[1]https://www.microsoft.com/en-us/research/video/holoflector/

volume of space under a two-way mirror, which reflects a monitor placed above it [21]. *Toucheo* used a similar setup for interaction with 3D objects using 2D metaphors [19]. While these works explored using mirror for AR in different ways, they mostly focused on augmenting the reflection without incorporating the physical space outside the mirror. In this work, we add an AR HMD to a smart mirror to blend the physical and the reflected space across the mirror for novel interaction affordances.

2.3 Interaction affordances of mirrors in AR

From the perspective of the viewer, a mirror "captures" the volume of space where they reside, and duplicates it back into the opposite direction. This interpretation reveals two conceptual affordances—the display of replicas of the objects and events in the physical space, and the extension of the physical space across its boundary with the reflection. For instance, the need to expand the limited interactive space in AR has been raised in previous works. McGill et al. explored different ways of expanding the bounds of seated virtual workspaces [34], while *One Reality* showcased a Mixed Reality ecosystem featuring 6 levels of incremental augmentation over the same physical space [44]. These use cases could benefit from yet another layer of augmentation over the pervasive mirror reflections.

Apart from expanding the perceivable space, mirrors enable their users to see their own body, which provides an intuitive spatial reference to visualise body-centric virtual augmentations. Previous works explored the arrangement of AR content within the egocentric spatial frame of reference around the body. For instance, Ens et al. introduced a layout manager that embeds virtual application windows in the user's surroundings while leveraging spatial memory of a known body-centric configuration [13]. Chen et al. proposed a body-centric technique that extends a mobile device's interaction space to mitigate the limitation in the field-of-view (FoV) while leveraging egocentric spatial perception [9]. Zhou et al. investigated user performance of acquiring egocentric targets without seeing them in a mobile VR setting, while benefiting from proprioception. They found that the performance was accurate when static, but worsens with increasing walking velocity [64]. Wagner et al. contributed *BodyScape*, a body-centric design space exploring the affordances of different body parts for multi-surface interaction [54]. Mirror reflections provide an intuitive and useful visual reference for such interfaces and design spaces, granting users the knowledge of the relationship between their bodies and virtual content in space, which is nearly impossible otherwise.

The reflected body in the mirror has other potential benefits for interaction beyond as a spatial reference. Recent advances in cognitive science suggest that the reflected body is treated as "special" in the mind compared with external objects in that it is directly related to the self [27, 28]. The space around the reflected body was found to be perceivable using an egocentric frame of reference in the same way as the real body [42]. While these works suggest benefits from seeing the body in the mirror as context, other evidence suggests that the reflected body may also be used to perform input. In recent studies, Mine et al. found that a disconnected hand avatar can be integrated into the peripersonal space which may represent the reference frame required for visuo-motor action using a specific body part [37, 38]. While it is known that tool embodiment is possible with training, it is plausible to perceive the reflected body as an intuitive tool for input during MR interaction with mirrors [7]. Such psychological characteristics of the mirror, and its benefit for visualising the user's body, could serve as a pervasive visual reference for novel body-centric interaction techniques, such as body-centric multi-surface interaction [54] and imaginary interfaces [18].

In this work, by combining an augmented smart mirror with an AR HMD, we contribute a novel design space that we define as reflected reality, and a proof-of-concept prototype as its instantiation. By connecting the physical AR space and its reflection in the mirror, reflected reality transforms the reflection in augmented smart mirrors into a full-scale AR space, and opens a new dimension of mirror reflections for traditional HMD-based AR. We demonstrate how our design space benefit from the spatial qualities of mirror reflection explored in the literature, such as providing context for interaction around the body, and using the reflected body as an avatar for bodily interaction.

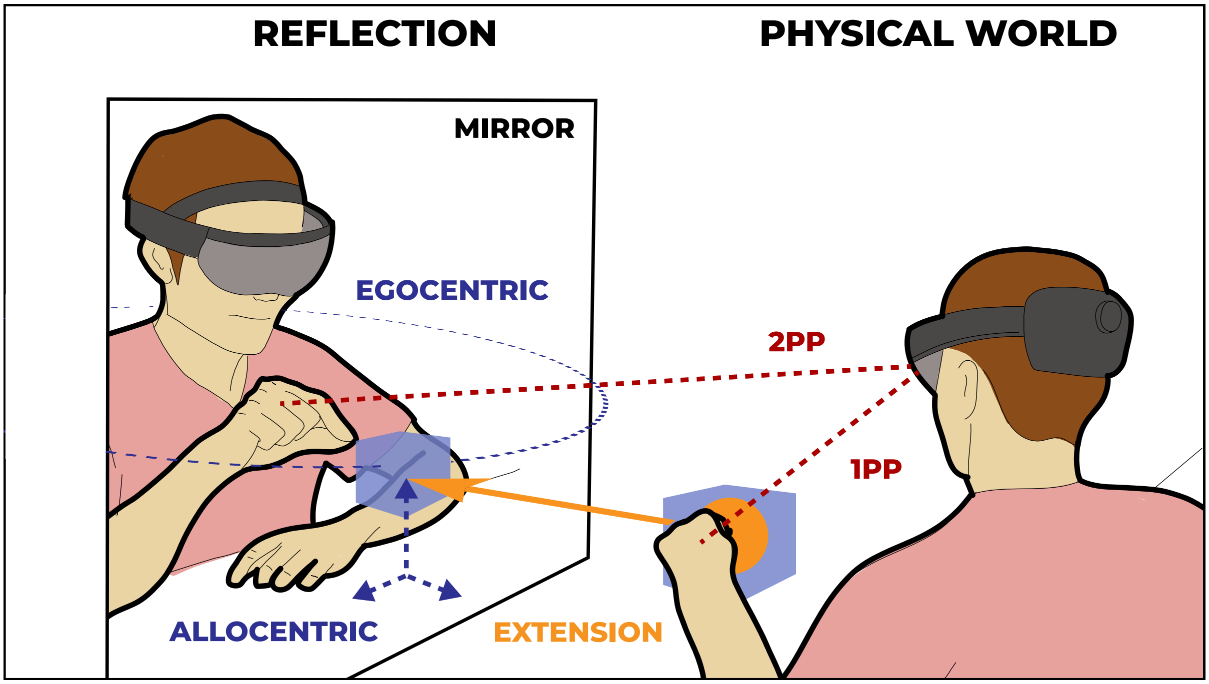


Fig. 2. Design space of reflected reality. Through the combination of the smart mirror and the AR HMD, users can perform interaction either from a *first-person* perspective (1PP) through the HMD, or from a *second-person* perspective (2PP) while using the reflected body as an avatar. The locations of the virtual objects in both spaces can be defined in an *egocentric* frame of reference relative to the physical and the reflected bodies, or in an *allocentric* frame of reference relative to the surrounding environment. The space in the mirror can be used as a *reflection* of the physical space, or as its *extension*, where users could reach through the mirror to remotely interact with objects in it, or to move objects between the two spaces across the mirror.

3 REFLECTED REALITY: DESIGN SPACE

In this section, we explore the design space of reflected reality based on the combination of an augmented smart mirror display and an AR HMD. The smart mirror tracks the physical space in front of it, and renders the virtual objects in that space over the mirror reflection. The AR HMD renders virtual objects in the physical space and in the reflected space, and provides spatial tracking for the two sides across the mirror as a continuous volume of space.

We define the design space along three dimensions (Fig 2): the Perspective taken by the user for input, either of their real body or of their reflected body in the mirror; the spatial Frame of Reference to define the locations of virtual objects, either relative to the users' bodies or to the surrounding environment; and the Direction of the reflected space in the mirror, either used as a pure reflection, or as an extended space that can be directly interacted with from outside the mirror. Following the definitions, we discuss the combinations of the design space elements in greater detail while instantiating it in a use case scenario (Figure 4a—6b).

3.1 Perspective

Perspective represents the perceived body that the user performs the interaction with. They either perceive the interaction from a *first-person* perspective (1PP) through the HMD, or from a *second-person* perspective (2PP) while perceiving the reflected body as an avatar of their physical body.

3.1.1 First-person perspective (1PP). The reflected space in the mirror can provide visual context when the interaction is performed from within the HMD. For AR applications that feature body-centric augmentation, users are able to observe the positions of and the relationship between the body-centric virtual objects in the mirror, with their reflected bodies as context from an exocentric perspective. For instance, to visualise a ring of objects floating around a part of their body, the user can move and rotate that body part to observe the occluded objects, such as those in the back. Because the mirror is placed at a further distance than the HMD, it also provides a larger FoV for visualising objects in the body space, which benefits the user when they need to arrange the objects around their body.

For instance, in interaction techniques similar to *The Personal Cockpit*, the mirror provides an alternative viewing port for users to visualise more virtual content around their body, and to locate them with less effort induced by head movement [14]. Finally, the smart mirror can also interactively show or hide reflections of virtual objects in front of the mirror. For instance, while users can manipulate a virtual object in front of the mirror to observe its virtual reflection in the mirror, they can also disable its reflection when they want to observe the different appearance of the augmented space with and without the object. These features make the reflected space a malleable context for 1PP interaction using the HMD.

3.1.2 Second-person perspective (2PP). Equipped with full-body motion tracking, users can gesture in mid-air to select and manipulate virtual objects located within the tracking space, similar to the implementation in previous works [20, 30, 33]. Borrowing from the analogy between linguistic point of view and user perspective in immersive applications, we use the term *second-person* perspective to describe situations in which users fully immerse themselves within the view inside the mirror while performing certain interaction tasks. We propose that in *reflected reality*, it is crucial to distinguish 2PP from the 1PP interaction used in the HMD, and from the 3PP commonly used in video games. In 2PP, whereas the user can perceive their reflected body as an “avatar" similar to 3PP video games, they perceive an avatar that is positioned across their 1PP physical body, sharing a duplicated volume of interactive space between them. This shared space, including the duplicated bodies, provides immediate context both for interaction performed using the perceived 2PP reflection avatar or using the 1PP physical body. Compared with 3PP, which usually provides the view of the back of the avatar, the addition of 2PP interaction enables users to seamlessly switch between 1PP and 2PP while interacting with objects located in the same volume of space in front of them by connecting the two sides across the mirror in reflected reality. Moreover, recent findings in psychology indicate that the reflected body in the mirror is perceived in a similar way to the physical body of the observers, in terms of the perception of the immediate space surrounding them [27, 28, 42]. Benefiting from these psychological phenomena, and from people’s familiarity with observing their reflections in mirrors, the reflected “avatar” has the potential of being intuitively controlled.

3.2 Frame of Reference

Frame of Reference represents how the objects are spatially anchored in the interactive space relative to the user—by using parts of their body (*egocentric*) or features of the environment (*allocentric*). Because the user’s body is in the visible reflection in most use cases of their daily interaction with mirrors, it is important for the user to be able to correctly anticipate how their body movement in front of the mirror induces the spatial updates of the virtual objects displayed on and in the mirror. The user must be aware of the spatial relationship between their body position, head (viewpoint) position, and the objects located in the surrounding space, to correctly locate and visualise them in the mirror for interaction. Similarly, users are able to find the mirror reflections of out-of-view objects in the physical space and get around the limited FoV of the HMD, only while being aware of which objects are in which frame of reference. For instance, when the user wants to interact with a virtual object attached to their forearm, they will be able to see it in the mirror, and lift their arm towards the HMD to access it, instead of looking for the object at the location where their arm used to be, within the allocentric frame of reference.

3.3 Direction

Direction concerns the direction of the reflected space behind the mirror that is used for interaction tasks. Users can use the space behind the mirror either as a pure *reflection* of the physical space, in which the objects and events are exactly copied, or as an *extension* of the physical space in front of the mirror, in which the users' actions outside of the mirror can directly take effect inside the mirror, not through reflection, but continuously across the boundary. For instance, a user can pick up a virtual object in front of the mirror and throw it across the mirror surface on the ground of the reflected room. This type of interaction is enabled by the merged tracking of the two spaces across the mirror in reflected reality (Fig 2), wherein the movement of virtual objects can be tracked continuously across the invisible surface of the mirror. The user may switch between using the two Directions of the mirror space for interaction tasks that are more difficult to perform otherwise.

4 PROTOTYPE IMPLEMENTATION

We present the design and implementation of a prototype system consisting of Unity applications developed to run on a custom-built augmented smart mirror display and a HoloLens 2 headset. This prototype demonstrates interaction tasks that instantiate all dimensions in the design space and unique affordances offered by the smart mirror. We opensource a reflected reality toolkit containing the code for calibrating and synchronising AR objects and their reflections across a mirror, which could be implemented using a HoloLens 2 or other AR HMDs with QR code tracking capabilities[2].

We built a smart mirror based on the standard setup of a two-way mirror glass mounted on top of a screen (for which we used a 65-inch LED TV) for overlaying virtual objects on the mirror reflection, similar to previous works [33, 46] (Figure 3). We used the Microsoft Azure Kinect sensor which provides a high-definition point cloud for room-scale spatial mapping and full-body motion tracking. For view-dependent rendering, we used the body (head) tracking function of the kinect sensor and built a Unity application to adjust the viewing perspective of the virtual screen content according to the viewing perspective of the user (Figure 3). In addition, a VR occlusion shader is applied to the point cloud of the user's body, so that the virtual objects behind the user are correctly occluded on the smart mirror. With spatial mapping, motion tracking, and view-dependent rendering, the smart mirror can be used as a standalone AR interface for basic bodily interaction using the reflected body.

For the HMD, we use a Microsoft HoloLens 2 headset to provide forward spatial mapping into the mirror. We establish a UDP connection between the smart mirror and the HoloLens 2, to update positions and rotations of a list of synchronised objects. The coordinates of the interactive tracking space in the HoloLens 2 are calibrated to match the spatial coordinates of the Azure Kinect's tracking. The HoloLens 2 reads a QR code shown on the centre of the smart mirror and gets its position [3]. Once the calibrated connection is established between the smart mirror and the HoloLens 2, the two devices share the centre of the mirror as the spatial anchor.

The prototype keeps three copies of any synced object—one displayed on the mirror, one in the HoloLens in front of the mirror, and one in the HoloLens behind the mirror—the rendering of which can be individually turned on and off to enable different types of interaction. The position and rotation of each copy of the objects are synced in real-time when any one of them are moved by the user. We disabled the spatial awareness feature of the HoloLens 2 to allow the remote selection pointer to travel through the surface of the mirror, extending the spatial tracking of virtual objects to the space behind the mirror [4].

[2]https://github.com/qiushi-zhou/Reflected-Reality-HoloLens-Selection
[3]https://localjoost.github.io/Reading-QR-codes-with-an-MRTK2-Extension-Service
[4]https://github.com/microsoft/MixedRealityToolkit-Unity

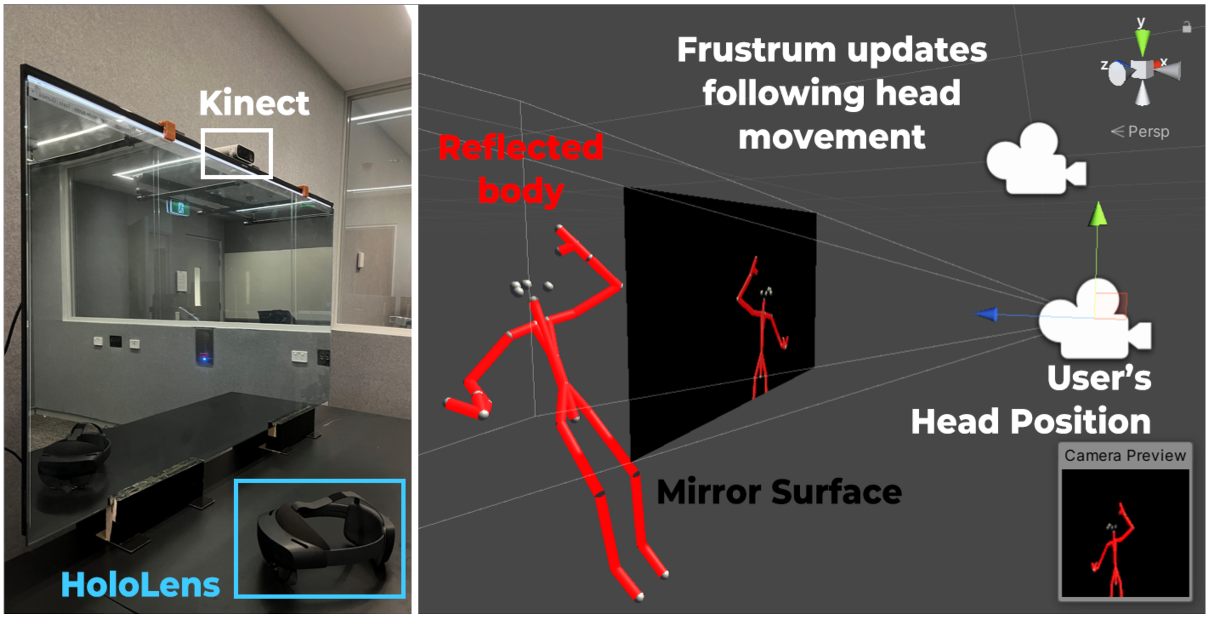


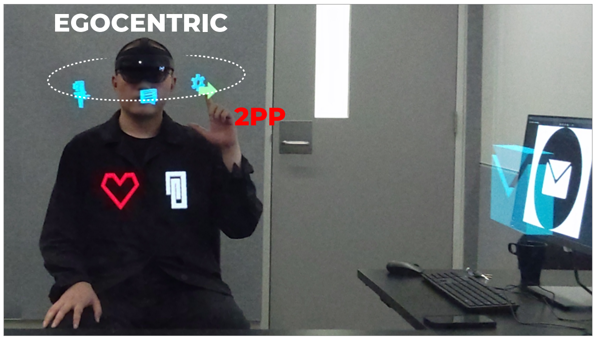
Fig. 3. Hardware and software configuration of the smart mirror in the prototype system. **Left**: the structure of the hardware setup consisting of a two-way mirror overlaid on a 65-inch LED TV screen. An Azure Kinect sensor is placed on top of the TV. **Right**: Software setup in Unity. A view-dependent render area is defined (the black quad) to show the virtual viewing area that matches the user's view of the mirror reflection, through head-tracking provided by the Kinect sensor.

5 USE CASE SCENARIO

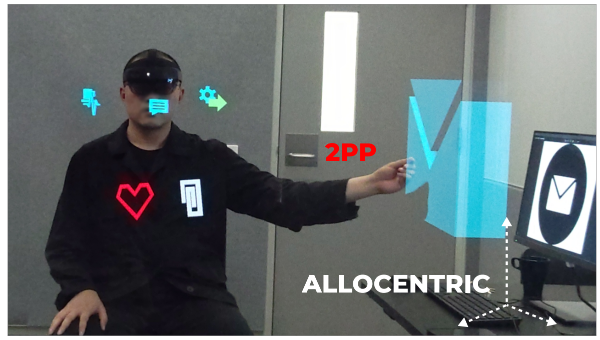
In this section, we visualise a use case scenario that instantiates the novel interactions supported in the design space of reflected reality. Please refer to the video submitted as supplementary material for a better understanding of the scenario. For easier comprehension of the relationship between the design space and the use case scenario, we divided the sequence of interaction tasks into six different combinations of the design space dimensions, and annotate the snapshots taken during those tasks using the design space elements. Please note that the texts, the dashed lines, and the orange arrows are annotations added to the snapshots (Figure 4a—6b). Using the tasks in the scenario as examples, we demonstrate how each possible combination of the reflected reality design space dimensions can afford novel and essential AR interaction in a generic daily context.

5.1 2PP + Egocentric + Reflection

The use case scenario is an interaction sequence using a reflected reality system in a fictional everyday context. The scenario starts with the user sitting in front of an ambient smart mirror, which is always turned on for information visualisation and augmentation of the reflected room. A heart and a paperclip are virtually attached to the reflected body of the user, and follow him as he moves around (Figure 4a). The paperclip represents a temporary container for objects intended to be opened in the HMD, and the heart represents a favourites folder for collecting objects of interest for future use. A ring of self-rotating blue icons are displayed around the user's head following his head movement and rotation. The users sees that the notification icon has turned to green, which indicates incoming messages. He pinches the icon with his reflected hand, while using his reflected body as a spatial reference to locate the icon.



(a) User pinches one of the floating icons. The notification icon turns to an arrow pointing to the side screen. User interacts with virtual object in the *reflection* space behind the mirror, in the *egocentric* frame of reference of the user, who performs *2PP* interaction while using their reflected body as an avatar.



(b) User grabs the virtual email rendered on the mirror as attachment to the side screen, and puts it in the paperclip. User interacts with virtual object in the *reflection* space behind the mirror, in the *allocentric* frame of reference of the user, who performs *2PP* interaction while using their reflected body as an avatar.

Fig. 4. *2PP + Allocentric + Reflection* and *2PP + Egocentric + Reflection* interaction in the reflected reality design space.

The above interactions are accomplished without the HMD. Using the smart mirror alone, the user is able to interact from 2PP using their reflected body, thanks to the motion tacking provided by the Kinect. Here, the smart mirror provides a unique exocentric visual access to the augmented body-centric space, while giving the user a holistic view of the virtual objects attached to their body (Figure 4a). The user is able to move their body and observe how the objects follow them in the egocentric frame of reference, and determine the approximate locations of the objects while using the body as a spatial reference. Most notably, the user is able to judge the depth of the icons, although they are rendered as 2D images. This could be achieved thanks to the sensorimotor contingency of the optical mirror reflection, and the visual occlusion of the virtual objects behind the user. By moving their head, the user can infer the change in position of the icons in 3D space based on the change in position of their own head, which is possible thanks to the parallax in mirror reflection, potentially building upon their intuition of how mirrors work. In this case, the physical world is context for the focus on the 2PP + Egocentric + Reflection interaction in the reflected space.

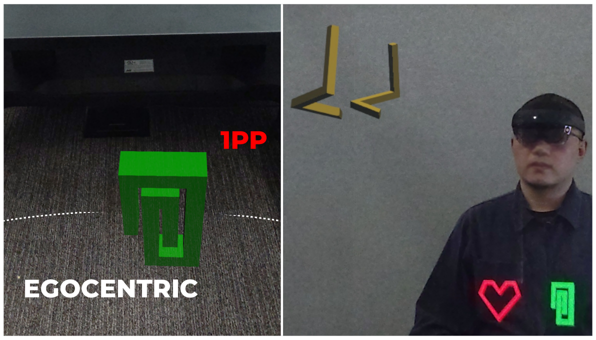
5.2 2PP + Allocentric + Reflection

Once pinched, the notification icon turns into an arrow. The user turns and sees the 3D email icon displayed over the monitor, then grabs the email and puts it inside the paperclip attached to his body to read in the HMD (Figure 4b).

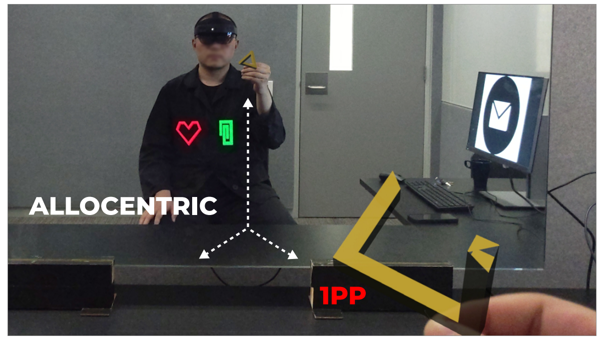
The user is informed of the existence and the position of the email object in the allocentric frame of reference by interacting with the notification icon within the egocentric frame of reference in the previous step (Figure 4b). In this case, while the user locates the email object in an allocentric frame of reference in the reflected space, the egocentric frame of reference is serving as context. First, the user finds the location of the email object by seeing the arrow indicating direction and moves their head to see it, and subsequently bring it to the paperclip on the reflected body. The possibility of this entire sequence builds upon people's familiarity with mirror reflection in their daily experiences.

5.3 1PP + Egocentric + Reflection

The paperclip turns green after the email enters, and a QR code shows on the mirror for calibration with the HMD. The user then enters *Reflected Reality* which reads the QR code to calibrate its tracking with the mirror. Then the user lowers his head to find the paperclip duplicated into the physical space, and touches it to read the first email (Figure 5a).



(a) User looks down and sees the paperclip copied to the physical space. The Penrose triangles appear after user touching the paperclip. User interacts with virtual object in the *egocentric* frame of reference, in the physical space in front of the mirror while using the *reflection* as context. User performs the interaction using their physical body, from *1PP* through the HMD.



(b) User grabs and manipulates the Penrose triangle through the HMD. User interacts with virtual object in the *allocentric* frame of reference, in the physical space in front of the mirror while using the *reflection* space behind the mirror as context. User performs the interaction using their physical body, from *1PP* through the HMD.

Fig. 5. *1PP + Egocentric + Reflection* and *1PP + Allocentric + Reflection* interaction in the reflected reality design space.

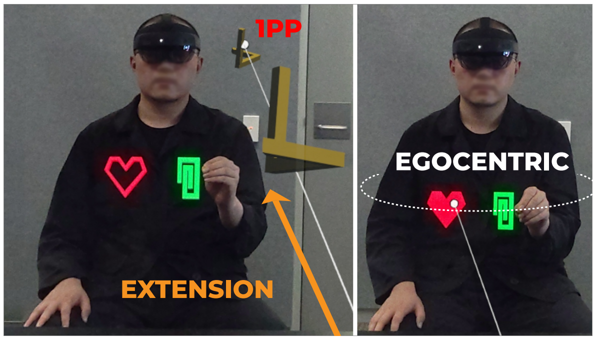
The first object copied to the physical space through the HMD is the paperclip originally attached to the user's reflected body (Figure 5a). The user is able to locate this object after seeing and interacting with it in the reflected body-centric space previously. Here, the interaction benefits from the human ability of seeing and recognising their own body in the mirror [27, 28], and transferring the egocentric spatial knowledge across the mirror surface [42]. With the smart mirror showing the locations of the objects attached to the body with the view of the full body as a context, the user can easily locate the reflected copy even though it just appeared. This way of visualising the augmented body-centric space is an potential solution to mitigate the limited FoV of HMDs, as the objects within that space tend to be often outside of the FoV, requiring substantial head movement to navigate and locate. Previous works such as *The Personal Cockpit* can benefit from this approach [9, 14].

5.4 1PP + Allocentric + Reflection

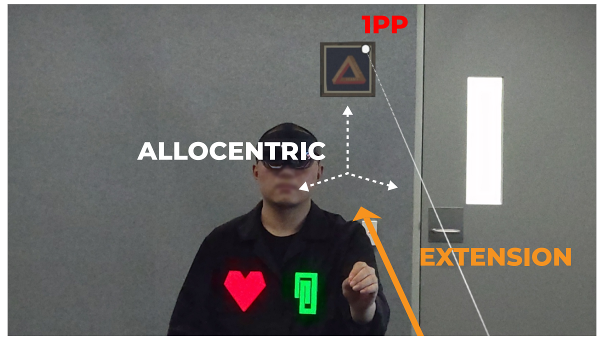
The email is displayed through the headset with an attachment of a *Penrose Triangle*,[5] which displays a visual illusion of an impossible shape that can only be observed from specific viewing angles. The triangle appears with a reflected copy behind the mirror (Figure 5a). The user picks up the triangle, manipulates it, and tries to observe the triangle and its reflection from different angles to understand its structure (Figure 5b).

After the triangle is created, the user freely moves and rotates it across the empty physical space in front of the mirror (Figure 5b). The synchronisation between the triangle in the physical space and its "reflection" created by the HMD in the reflected space enables the user to observe both images simultaneously to understand its structure. Because the spatial tracking of the HMD is calibrated with the mirror, the virtual reflection of the object appears as if it is being manipulated by the reflected body at the same time. This allows the user to potentially switch their perceived interaction between manipulating the triangle from 1PP using the physical body and from 2PP using the reflected body.

[5] https://www.illusionsindex.org/i/impossible-triangle



(a) User puts the reflected triangle in the heart attached to the reflected body. User interacts with virtual object in the *egocentric* frame of reference, in the reflected space behind the mirror, which is used as an *extension* of the physical space in front of the mirror. User performs interaction using their physical body, from *1PP* through the HMD.



(b) User moves object from physical space into reflected space. User interacts with virtual object in the *allocentric* frame of reference, in the reflected space behind the mirror, which is used as an *extension* of the physical space in front of the mirror. User performs interaction using their physical body, from *1PP* through the HMD.

Fig. 6. *1PP + Egocentric + Extension* and *1PP + Allocentric + Extension* interaction in the reflected reality design space.

5.5 1PP + Egocentric + Extension

After the user finishes observing the triangle, he decides to save it in the favourites folder (heart icon). He does this by pointing through the mirror into the reflected space and selecting the reflected triangle, subsequently putting it inside the favourites folder attached to his reflected body. The heart turns full as the triangle enters and disappears (Figure 6a).

When used as extension, the entire reflected space becomes available for 1PP interaction, including the reflected body and its surrounding virtual augmentation. When performing 1PP interactions across the mirror in *extension*, the reflected body acts as a moving frame of reference for some objects in the reflected space, controlled by the user. In this case, the user can select the reflected triangle remotely using the hand ray in the HMD and moves it into the heart container (Figure 6a). This type of interaction is useful for arranging virtual objects in egocentric AR applications because users are able to directly select and manipulate the objects across the mirror while seeing the whole picture as a visual reference [9, 14]. Additionally, with the possibility of using the reflected space as an extension of the physical space, interaction with objects in the body-centric space can be performed either from 1PP or 2PP, or concurrently. For instance, when moving virtual objects in the mirror between the body-centric space and its surroundings, the user can select objects remotely with 1PP, and select the body-centric objects with 2PP using their reflected hand, in situations where the target object is occluded from being reachable using 1PP remote-selection from the physical space.

5.6 1PP + Allocentric + Extension

The user then touches the paperclip again to bring up the second email with an attachment of a virtual framed picture of the same triangle. The user decides to “hang" it on the wall reflected in the mirror. Because the virtual picture was intended to be viewed on the smart mirror (which stays on without the HMD), the user must see the reflected wall in the mirror to find a place where he would be able to see later while sitting here. So he grabs the picture, remote-selects it, and pushes it into the reflected mirror space and hangs it. As the picture hits the reflected wall, it renders on the smart mirror and remains after the user quits the app on the HMD (Figure 6b).

When used as an extension of the physical space, the entire reflected room becomes an additional volume of space available for 1PP interaction directly from the HMD. This addition of the volume of the interactive space is more than doubling the original interactive space between the physical body and the mirror surface (Figure 2). Because the smart mirror adds another layer of display for virtual objects in addition to the HMD-rendered objects inside and outside of the mirror, the user is now able to modify virtual augmentations of the reflected room and make it take effect on the smart mirror even after they quit the HMD app. In this case, while the user obtains the virtual picture from interaction with the HMD, its reflection is not immediately rendered in the HMD by choice (Figure 6b). This is because the virtual picture is intended to be sent to the smart mirror from the HMD, while rendering its reflection may cause confusion when it travels across the boundary between the physical space and the mirror space. The optional rendering in the current setup of the prototype system uniquely affords such interaction to allow the physical space, the reflected space, and the smart mirror display space to be modified separately and synced when necessary. In this case, the user has to "hang" the virtual picture on the wall by pushing it through the mirror into the reflected space, because they can only know if it would be within view of the mirror by looking at the mirror while they find a place for it. The extension space from 1PP affords more complex interaction through the HMD with objects in the reflected space than what the 2PP interaction affords, at places where 2PP interaction cannot reach.

5.7 2PP + Extension and other possibilities of the design space

5.7.1 2PP + Extension. Though it is not as intuitive to find practical use for 2PP + Extension design space dimensions in the current scenario, we discuss them here for a comprehensive design space exploration. 2PP + Extension could be useful for playful interaction that challenges the user to accurately select virtual objects rendered in the physical space. Such input can be performed using a hand ray (originated from the reflected hand) that extends across the mirror surface. Another layer of complexity could be added to this type of playful interaction by incorporating body movement of the user in front of the mirror, while selecting targets rendered in the egocentric frame of reference that move with the user's body, and targets rendered in the allocentric frame of reference that remain in space despite the user's movement.

5.7.2 Other possibilities. Other than direct manipulation and hand ray, additional input modalities could be incorporated in reflected reality interaction. For instance, gaze input could be implemented with a reflected reality setup by translating gaze directions into the reflected space in the software. Gaze is an intuitive input modality that naturally extends through the mirror surface and falls on objects and surfaces in the reflected space. In reflected reality, gaze can support manual input to enhance its capabilities for generic 3D object manipulation [57]. It can also be utilised for ubiquitous interaction with appliances in domestic environments in a similar way to previous explorations [53], while only requiring a fixed eye tracker installation with a mirror on a wall (instead of a wearable eye tracker), which "reflects" the gaze onto the intended objects.

Multi-user scenario is another area to explore with reflected reality. For single physical user, virtual collaborators could be rendered in the mirror to support remote virtual collaboration without the need to wear MR headsets [23]. While it only makes sense for a single physical user to use reflected reality at a time (because of how view-dependent rendering works), multiple physical users can use reflected reality in turns. In these cases, whereas everyone would be able to see the information rendered on the smart mirror, they would have private views through the headsets. This asymmetry of privacy enables the exploration of interaction techniques similar to a metaphor of public (smart mirror) and private (headset) keys, where the outcome of interaction with the same virtual object rendered on the smart mirror could be rendered differently through the headsets, and only accessible by each individual user [45].

6 EXPLORATORY EVALUATION

To understand how users may perceive and perform the novel interaction techniques afforded by the reflected reality design space, we conducted an exploratory evaluation study to gain insights from their subjective feedback while being guided through the interaction sequence in the scenario. Through the evaluation, we aim to identify main characteristics of reflected reality around its design space dimensions that challenge users' perception of the spatial relationship between virtual objects in physical space and in the reflected space. We later unpack these characteristics into a subsequent formal evaluation to investigate their effects on user interaction performance in a more controlled setting. Both studies were conducted under the approval of the Human Ethics Committee at our university.

6.1 Participants

We recruited 12 participants (5 women, 7 men) with a mean age of 26.9 years ($Min=22, Max=34, SD=3.3$) through university mailing lists. The study lasted approximately 40 minutes on average, with a $20 gift card compensation. On a scale from 1 (rarely) to 7 (daily), users rated their experience with mixed reality as 3.5 on average ($SD=2.1$).

6.2 Procedure

Upon arrival, we introduced participants to the purpose of the study and the functionality of the prototype. Then, we described the use case scenario in Section 5 to the participants, while playing a pre-recorded video, which shows a walk-through of the sequence of interaction. Then, participants attempted to finish the tasks in the scenario themselves, while following the instructions from the experimenter. At the end of the scenario, we asked the participants to describe their experience in the following aspects of the design space: *How was your experience different in performing input from different perspectives (1PP/2PP)? How was your experience different in interacting with objects placed in different spatial frames of reference (egocentric/allocentric)? How was your experience different in performing input while using the space behind the mirror in different directions (reflection/extension)?* Finally, we asked participants for generic feedback, and to rate their overall experience using the User Experience Questionnaire (short version) [48].

6.3 Results

We present common issues and interesting comments raised in participants' response to the interview questions, along with the results from the UEQS questionnaire (Figure 7).

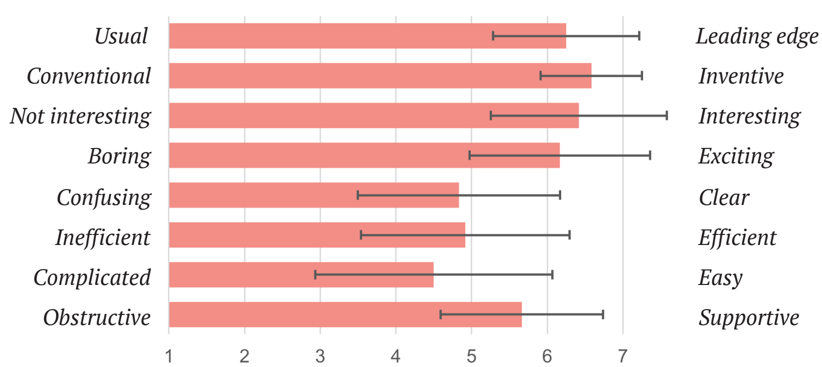


Fig. 7. Results of the User Experience Questionnaire

6.3.1 *User experience with* Perspective.

Eight participants considered 2PP input as intuitive as 1PP input, four of which explained that the intuitiveness benefited from their daily experience of looking at themselves in mirrors. P5 suggested that the larger FoV provided by the mirror made 2PP interaction easier, while P7 liked the additional exocentric perspective of 2PP. P2 and P3 pointed out that it was harder to perceive the distance of the objects in 2PP.

6.3.2 *User experience with* Frame of Reference.

Seven participants preferred seeing and interacting with egocentric objects in the mirror, to interacting with them in the physical space (i.e., with the paperclip). They explained the primary reason as because those objects tend to be out of the limited FoV of the HoloLens, whereas the mirror provides a much bigger FoV with the reflected body being a visual reference for them.

6.3.3 User experience with Direction. Five participants considered performing input across the mirror surface (extension) as easy and intuitive as performing input within either side of the mirror. Three participants acknowledged the benefit of direct 1PP interaction with objects in the reflected space, for the better FoV afforded by the mirror. P4 pointed out that it was especially helpful for interacting with objects behind their bodies without turning around, because they could remotely access their reflections in the mirror, such as in the task of hanging the virtual picture on the reflected wall (Fig 6b). P8 and P11 preferred 1PP + extension input over 2PP input because the movement direction of the bodies and the objects along the Z axis (towards the mirror) in the former is consistent with the physical space, whereas the direction is flipped under 2PP perception as the opposite to the physical space. P1, P4, and P12 appreciated the use of mirror reflection as an extension to the physical space to afford more possibilities of interaction.

P3, P6, and P8 observed that the objects in the mirror are further from their hands while performing 1PP input than when performing 2PP input, which demanded more precision in the remote selection using the hand ray of HoloLens 2. P3, P6, and P8 said that the non-stereoscopic rendering of the heart icon made it harder to perceive its distance while attempting to place the triangle in it (Fig 6a).

6.3.4 General Feedback. In the end, four participants commented that the interaction was “fun", “engaging", and “cool." P5 and P6 commented that reflected reality is the only form of AR currently available that enables its users to see their bodies in the augmented space, and to create an extended volume of space for intuitive interaction. However, six participants mentioned that the non-stereoscopic rendering of objects on the smart mirror made it harder to locate those objects in the 3D reflected space, especially when attempting to make contact with them using other objects that are rendered stereoscopic through the HMD.

6.4 Discussion

The positive UEQS scores and feedback showed excitement and interest in reflected reality from the participants. However, the mixed scores and comments on clarity, efficiency, and ease of the interaction indicated the need to better understand the main characteristics of reflected reality, and their effects on usability.

Specifically, the second-person **Perspective** was one of the main characteristics that participants commented on about the intuitiveness of input using their reflections. The participants who liked 2PP input commented that it was due to their daily experience with mirror that provide **Visibility** of physical objects and their reflections. The input **Modality** (manual or remote through the hand ray) was also mentioned to have affected the ease of selecting virtual objects from a 2PP. Finally, many participants mentioned the extended **FoV** for rendering virtual objects in the mirror as a major benefit for finding AR objects outside the FoV of the HMD, or even out of sight.

7 FORMAL EVALUATION

Through the exploratory evaluation study, we identified characteristics of reflected reality interaction that demand further investigation in a controlled setting. We categorise their implications into two types, namely the intuitiveness of input from 2PP and the benefit of the extended FoV in the mirror. In this study, we aim to characterise the usability of reflected reality interaction to explicate its strengths and limitations for future applications.

7.1 Study Design

We designed and conducted the study using standard target selection and visual search tasks, which capture the general ease and intuitiveness of performing AR input and the benefits offered by the extended FoV in the mirror. These two tasks represent common primitive actions that make up other more complex interaction tasks performed in extended reality contexts [31, 51, 59, 60].

7.1.1 Target Selection. Learning from the exploratory evaluation, we found 2PP input to be a major source of difficulty perceived by participants with reflected reality interaction. To investigate this, we operationalise three factors with potential impact on target selection performance from 2PP, using a 2×2×2 repeated measures design:

PERSPECTIVE represents the viewing perspective that the participants take when performing target selection:

- 1PP for when participants select targets using a pointer or a ray attached to their physical body;
- 2PP for when participants select targets using a pointer or a ray attached to their reflected body.

MODALITY represents the two main input modalities used for performing target selection in AR:

- MANUAL where participants use a pointer attached to the tips of their index fingers to collide with the targets;
- REMOTE where participants use a ray attached to their hand to point at the targets and pinch to select them.

VISIBILITY represents the consistency between the virtual dimension of reflected reality and the optical reflection:

- DOUBLE where the targets in the physical space and their reflection behind the mirror are both rendered;
- SINGLE where only the targets being selected are rendered, either in the physical space or in the reflection.

7.1.2 Visual Search. Participants mentioned the extended FoV for rendering AR content in the mirror as a major benefit for different types of interactions, especially for visualising AR objects close to the body and out of sight. To empirically validate this benefit, we operationalise it as two conditions in a visual search task in AR, where participants search for one out of many targets populating the space around their bodies in front of the mirror, while they either see all the reflected targets in the mirror REFLECTION, or only see the targets in the physical space with NO REFLECTION.

7.2 Apparatus and Tasks

We used the same hardware and software setup described in section 4, while using the HoloLens 2 exclusively for rendering virtual objects in this study. During the entire study, participants were seated at a 1.5 m distance from the mirror on a chair adjusted such that they directly face the centre of the mirror when looking forward.

7.2.1 Target Selection. We employed the standard ISO 9241 pointing task [12] using 11 targets and measured completion time as performance (Figure 8 (a)) [6]. We used 2D circular targets (3.2 cm diameter) instead of 3D spherical targets to better control for the distance between the targets and the participants. We only allowed selecting the targets in the same side of the mirror with the current input perspective. They were placed in the physical space at 0.5 m in front of the participants during 1PP conditions, and in the reflected space at 0.5 m in front of the participants' reflected bodies during 2PP conditions. The targets were arranged in a ring with a radius of 0.5 m, while the current target to select is highlighted in red. In MANUAL selection, participants used a blue spherical pointer (1 cm diameter) attached to their index fingertips to collide with the targets (Figure 8 (c)) [6]. For REMOTE selection, we implemented a blue hand ray to override the hand ray in HoloLens 2 that points towards the direction of the hand (Figure 8 (b)). We used a pinch gesture between the thumb and the index finger to confirm the selection while the hand ray is hitting the desired target, while imitating the HoloLens 2 hand ray interaction. In the 2PP conditions, the pointer and the ray were rendered on the reflected hands of the participants in the mirror (Figure 8 (b)). The targets were rendered in 0.3 opacity to allow participants to see the pointer and the hand ray in the mirror when they are occluded by the targets. The ordering of the conditions was counter-balanced using a Latin Square. Participants were instructed to finish the task as fast as possible. Each condition of the task was performed with two repetitions (rings).

7.2.2 Visual Search. We designed a simple visual search task learning from previous work [51]. We employed spheres with diameters of 10 cm as search targets and distractions. At the start of each trial, 120 spheres were generated at random locations within the volume of the extended viewing frustrum of the participant in the mirror reflection, starting from 0.2 m away from the mirror, and ending at 2.5 m away (Figure 9 (a)). This is to ensure that all spheres could be seen by the participants as reflected in the mirror. To prevent collision with participants' bodies, no sphere was rendered below the headset, within 0.4 m distance to its left or right, or within 0.2 m in front of or

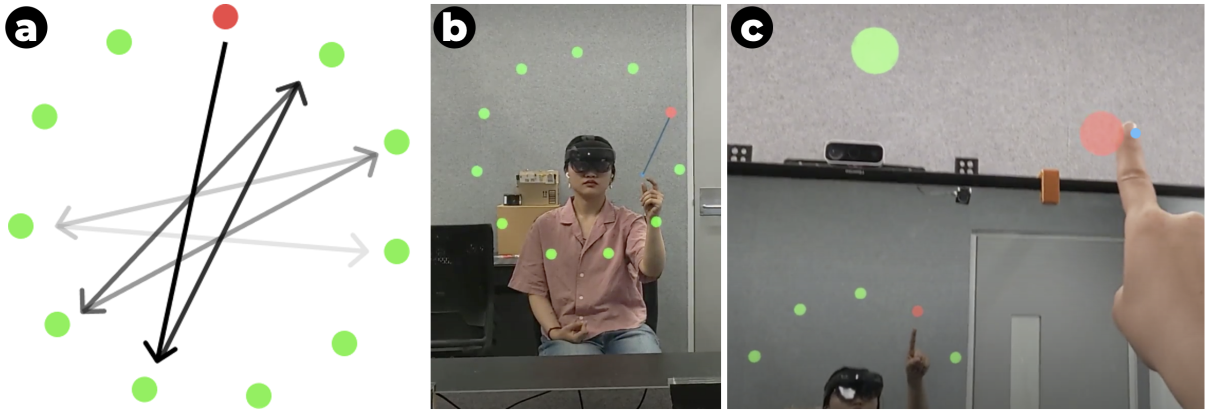


Fig. 8. Target selection task: (a) ISO 9241 pointing task with 11 targets. The current target is highlighted in red, and the targets are traversed clockwise; (b) Example condition showing a participant using the blue hand ray to Remote select a target in the mirror from 2PP while only seeing the targets rendered on the Single side of the mirror. (c) Example condition showing a participant using the blue pointer to Manual select a target in the physical space from 1PP while seeing the targets in Double sides of the mirror.

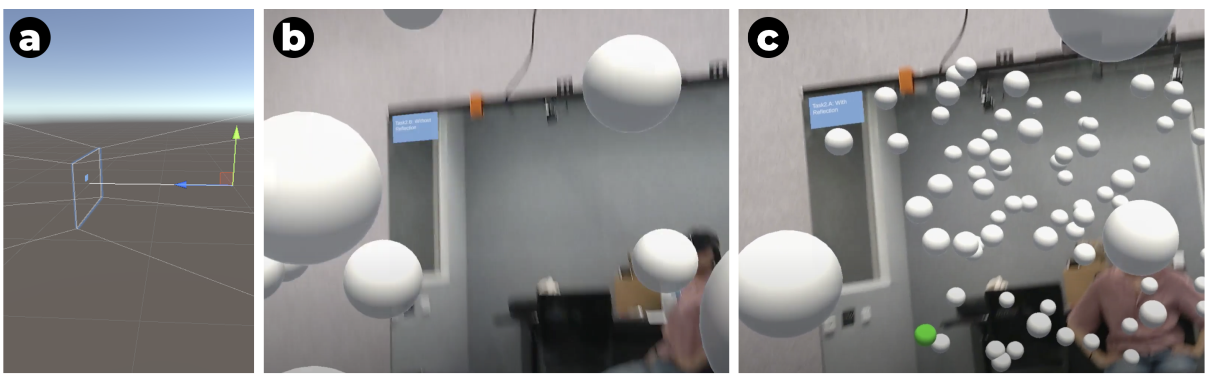


Fig. 9. Visual Search task: (a) The extended viewing frustrum within which the spheres were generated at the beginning of each trial; (b) Example No Reflection condition showing distractions around the participants in the physical space. (c) Example Reflection condition showing distractions around the participant in the physical space, and the reflected target and distractions in the mirror.

behind it. The target was randomly chosen among all spheres and was rendered in green, while the others were distractions in white. In the No Reflection condition, participants could only see the spheres surrounding them in the physical space in front of the mirror (Figure 9 (b)). In the Reflection condition, participants could also see the reflections of the spheres rendered in the mirror when they fell within the current view frustrum (Figure 9 (c)). The participants could rotate the chair and move their upper body to look around and search for the target. Once they found the target in the physical or reflected space, they needed to use the hand ray to remotely select the target in the physical space to finish the current trial. Each condition was repeated for five trials with different randomly generated spheres. The ordering of the 2 conditions was counter-balanced using a Latin Square. We measured search time, defined as the time taken from the moments when the targets were rendered to the moments when they were selected, as the task performance. Participants were instructed to find and select the targets as fast as possible.

7.3 Participants

We recruited 24 participants (13 women/11 men) with a mean age of 24.8 years ($Min = 19, Max = 37, SD = 4.34$) through university mailing lists. The study lasted approximately 50 minutes on average, with a $20 gift card compensation. Participants rated their experience with mixed reality (including VR and AR) interaction prior to the study on a 7 point Likert scale (1 being never, 7 being daily), with a mean rating of 1.88 ($Min=1, Max=4, SD=0.61$).

7.4 Procedures

Upon arrival, participants were informed of the purpose of the study and asked to sign a consent form. We instructed participants to sit at the designated location. To familiarise participants with the HoloLens 2 interactions and with the tasks, we started with a training session. After the experimenter calibrated the HoloLens 2's spatial mapping with the mirror, they put the headset on the participants and taught them how to perform hand interaction in HoloLens 2. Participants were then guided to practise each type of target selection technique (Perspective x Modality for target selection, and both conditions for visual search) until they were familiar with it, then proceeded with the formal trials. At the end of each condition, participants rated the ease of the task using the Single Easement Questionnaire [47]. After finishing all conditions in each task, we conducted a semi-structured interview, during which the experimenter asked participants for any perceived difference in performing the interaction tasks across different (Perspective, Visibility, Modality) conditions, as well as any other feedback, to gain further insights.

7.5 Results

We collected 3,840 target selection data points (24 participants × 2 Perspective levels × 2 Modality levels × 2 Visibility levels × 10 targets × 2 repetitions) with 384 easement ratings, and collected 240 visual search data points (7 participants × 2 Condition levels × 5 repetitions) with 48 easement ratings. For the performance of both tasks, we applied the Tukey's Ladder of Powers transformation [52] after identifying non-normal distribution of residuals. We subsequently applied the Aligned Rank Transform (ART) on the target selection performance data due to the persisting violation of residual normality and homoscedasticity [56]. Next, we performed a Repeated-Measures ANOVA with the task performance, and post hoc pairwise comparisons with Holm–Bonferroni adjustment. With the Single Easement Questionnaire ratings, we performed an Ordinal ANOVA [10] for the target selection task, and a Kruskal-Wallis Test [36] for the visual search task. We present the task performance data and all the statistically significant interaction effects in Figure 10—13, in which the error bars indicate 95% confidence interval.

The interviews generated around 120 minutes of audio recording. Two researchers, including the experimenter, carried out a general inductive analysis of the data, using independent parallel coding to categorise notable comments as quotes [49]. This was followed by collaborative tagging and discussion around the findings on a spreadsheet. The analytic process led us to a shared understanding of the potential sources of the perceived utilities and drawbacks of different features of reflected reality. We summarise the frequently occurred themes in Table 1.

7.6 Target Selection

For performance, all factors had significant effects, including Perspective ($F_{1,3809} = 259.87, p < .001$) with the time in 1PP ($mean = 2099.77, sd = 977.06$) significantly less than in 2PP ($mean = 3221.44, sd = 4501.37$); Modality ($F_{1,3809} = 904.21, p < .001$) with the time in Manual ($mean = 2036.6, sd = 1952.92$) significantly less than in Remote ($mean = 3284.62, sd = 4153.71$); Visibility ($F_{1,3809} = 12.56, p < .001$) with the time in Double ($mean = 2590.72, sd = 3319.55$) significantly less than in Single ($mean = 2730.49, sd = 3288.94$) (Figure 10). We found a significant two-way interaction between Perspective and Modality ($F_{1,3809} = 41.2, p < .001$) (Figure 11 (a)), a significant two-way interaction between Visibility and Modality ($F_{1,3809} = 13.04, p < .001$) (Figure 11 (b)), and a significant three-way interaction between Perspective, Visibility, and Modality ($F_{1,3809} = 27.1, p < .001$) (Figure 11 (c-d)).

Task	Participants	Theme
Target Selection	9	It was difficult to select targets from 2PP.
	6	The reflections help with target selection in the physical space.
	6	It was easy to select targets using the fingertip.
	6	It was difficult to use the hand ray from 2PP.
Visual Search	19	The reflections were helpful for finding targets.
	8	The mirror made it easier to locate targets out of the FoV of the headset.

Table 1. Common themes emerged from the post-task interviews by participants.

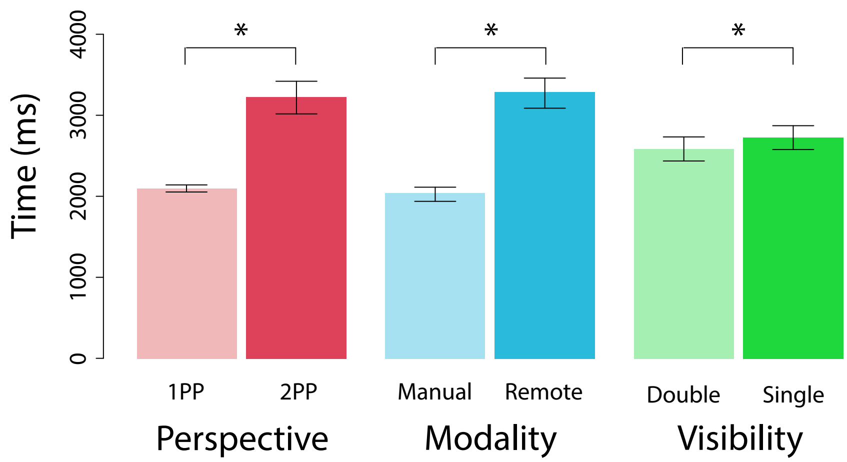


Fig. 10. Performance results of target selection across PERSPECTIVE, MODALITY, and VISIBILITY

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For the ratings of the ease of the selection task, the effect of PERSPECTIVE was significant ($\chi^2_1 = 47.79, p < .001$), while the ratings in 1PP ($mean = 6.16, sd = 0.93$) is significantly higher than in 2PP ($mean = 4.76, sd = 1.65$). The effect of MODALITY was significant ($\chi^2_1 = 33.24, p < .001$), while the ratings in MANUAL ($mean = 5.98, sd = 1.22$) is significantly higher than in REMOTE ($mean = 4.94, sd = 1.6$). The effect of VISIBILITY was significant ($\chi^2_1 = 5.18, p < .05$), while the ratings in DOUBLE ($mean = 5.63, sd = 1.52$) was significantly higher than in SINGLE ($mean = 5.29, sd = 1.49$) (Figure 12).

7.7 Visual Search

There was a significant difference between the two conditions ($F_{1,23} = 58.48, p < .05$) with the time in REFLECTION ($mean = 10813.08, sd = 12972.87$) significantly less than in NO REFLECTION ($mean = 26682.62, sd = 30595.54$).

For the ratings of the ease of the visual search task, there was a significant difference between the two conditions ($\chi^2_1 = 15.86, p < .001$) with the ratings in REFLECTION ($mean = 5.88, sd = 1.23$) significantly higher than in NO REFLECTION ($mean = 3.85, sd = 1.69$) (Figure 13).

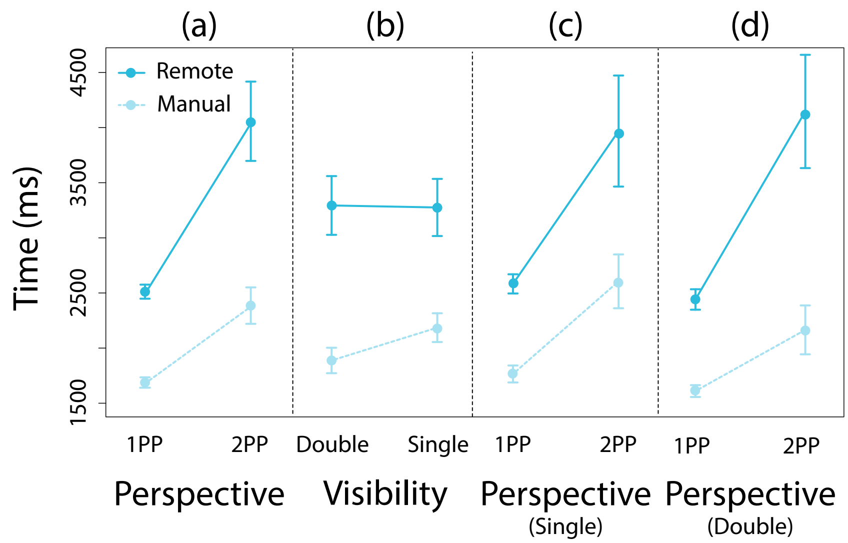

Fig. 11. Interaction effects in target selection performance: (a) Interaction between Perspective and Modality; (b) Interaction between Visibility and Modality; (c-d) Three-way interaction separately plotted in Single (c) and Double (d) Visibility.

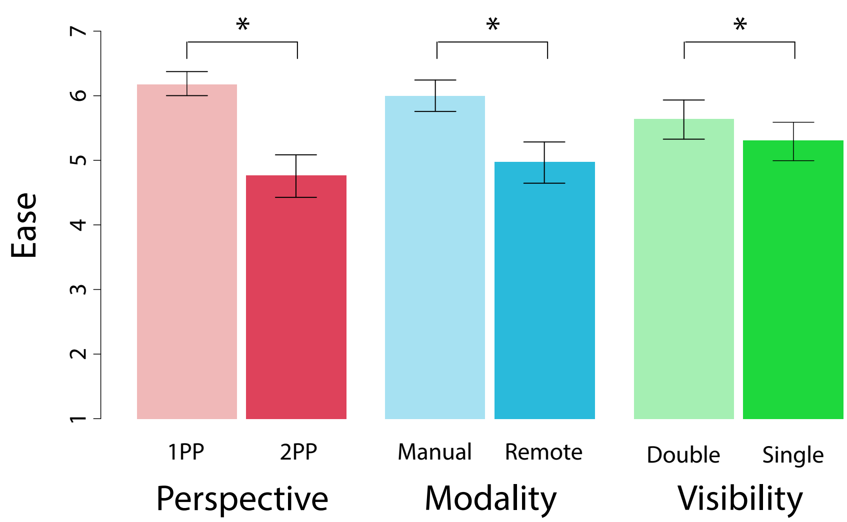

Fig. 12. Results of the Single Easement Questionnaire on a 7 point Likert Scale across Perspective, Modality, and Visibility.

7.8 Discussion

7.8.1 Target Selection. The statistically significant main effects in performance results (Figure 10) shows a mean value of 1121.67 ms difference between 1PP and 2PP, while the 2PP conditions were perceived by the participants as more difficult than 1PP with a 1.4-point difference on the 7 point Likert scale (Figure 12). This was supported by feedback from nine participants during the post-task interviews, that "*Selection in the real world is much more intuitive.*" (P3); "*Target locations in the mirror could be confusing.*" (P10), etc.. The significant main effect in the performance and

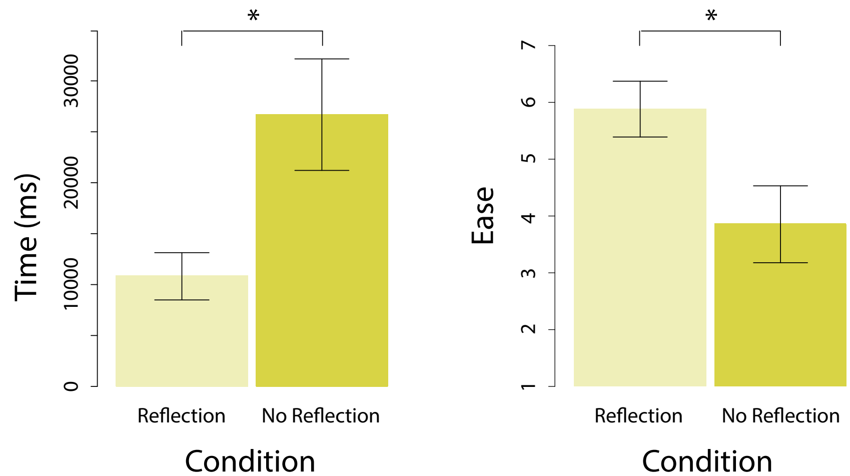

Fig. 13. Performance results (left), and Single Easement Questionnaire results (right) of the visual search task.

rating results for Visibility suggests that seeing the targets on both sides of the mirror helps participants perform better and feel easier while selecting targets, possibly due to its similarity to natural mirror reflection experiences, or because the visibility on both sides of the mirror enabled the participants to quickly switch their attention between their physical and reflected hands when necessary. P9 specified that "*It (seeing the reflected targets while selecting targets in the physical space during Double) saves time because there is no need to look around for the whole ring due to the limited FoV.*" Whereas the main effect in Modality does not offer direct insight into the usability of reflected reality interaction, it helps us understand the impact of input modality on its interaction effects with the other factors.

The significant two-way interaction effect between Perspective and Modality shows that the difference between the performance in 1PP and 2PP is more pronounced in Remote selection than in Manual selection (Figure 11 (a)). This indicates that while Manual input is more intuitive and easier to use than Remote input in general, it is more so for 2PP input. This is potentially due to the extra difficulty of using the reflected hand ray from the opposite direction at a distance, comparing with directly touching them using their reflected hand, which is more similar to their interaction with mirror reflections in daily life outside of AR. This was supported by feedback from six participants that it was especially difficult to use the hand ray to select objects remotely from 2PP: "*The blue (hand) ray is hard to control, particularly from in the mirror. It was fine from the physical space, and the fingertip was fine from both perspectives.*" (P4); "*It was more difficult to use the ray because it was hard to adjust the direction from within the mirror.*" (P19). In a recent study conducted using a similar technical setup, the performance of remote target selection using a hand ray was reported to be 2.24 seconds on average [55]. This is similar to the performance in the 1PP+Remote condition in our study, whereas the performance in 2PP+Remote was much worse (Figure 11(a)). This suggests that whereas the hand ray interaction yielded similar performance to previous work from 1PP, using it from 2PP seemed to have made it more difficult. Further, we could observe that the performance in 2PP+Manual conditions is close to that in the 1PP+Remote conditions, indicating that 2PP in reflected reality could be helpful in enabling users to manually select and interact with objects that are at far distances from users. For instance, P1 mentioned that "*I feel closer to the targets when using the fingertip to select them in the mirror.*" This is another potential benefit of reflected reality, which extends the AR space into the mirror and provides the reflected body from 2PP as an alternative input tool for interacting with AR objects in the space behind the mirror.

The two-way interaction effect between Visibility and Modality shows that the main effect in Visibility is mostly caused by the results in Manual conditions than Remote, which shows a slight opposite trend (Figure 11 (b)).

This effect is further explained by the three-way interaction, which shows that this difference in 2PP is more pronounced than in 1PP. Even though the virtual pointer was only rendered on single side of the mirror, seeing the physical and the reflected hands moving towards the targets synchronously may still allowed participants to benefit from switching their attention between the two hands, to potentially help them find the targets faster from 2PP, whereas the same effect could not have been achieved in REMOTE conditions, in which the hand movement was minimal. This suggests that users can benefit from seeing AR targets and the reflections rendered in the mirror to interact with them more easily by using their physical and reflected bodies as moving spatial frames of reference for each other.

7.8.2 Visual Search. The significant differences in the performance and the easement rating results indicates that the visual search task is easier with the reflections of the targets rendered in the mirror than without (Figure 13). This evidence clearly shows the benefit of the extended FoV provided by mirror reflections not only through getting around the FoV limitations of the AR HMDs, but also through visualising virtual objects in the whole volume of space around users all at once, saving them the trouble of turning around to find AR objects above, behind, or close to their bodies. This is supported by feedback from six participants who specified that the mirror made the visual search task easier primarily thanks to the expanded FoV, which enabled them to locate targets close to (P1, P10, P14), above (P8), or behind (P19) their bodies, and made them identify the target faster without looking around (P13, P21, P23).

8 DISCUSSION

We summarise the interaction affordances enabled by reflected reality as demonstrated by the instantiation of the design space through the prototype and the scenario, and discuss them in light of the evaluation results. By annotating and analysing the use case scenario from the perspective of the design space, we visualised how the virtual augmentations and interaction events happening in the physical space and in the reflected space can be used as context for each other. This is enabled by the unique configuration of the reflected reality setup, in which the smart mirror and the HMD together track virtual objects synced across a continuous volume of space covering both sides across the mirror (Figure 2). While the potential benefits of this setup are not limited to the interaction techniques we illustrated so far, we elaborate on those covered in the scenario, and discuss the novel interaction affordances enabled by reflected reality, which are difficult or impossible to achieve by using an augmented smart mirror or an AR HMD alone. Finally, we also discuss the potential of reflected reality for future applications.

8.1 Reflection: duplicated bodies and their perspectives

Viewing the reflected body is the most common use of mirrors in domestic spaces. Because of this (as mentioned by participants in the exploratory evaluation), users are able to intuitively perceive the movement of their reflected body behind the mirror as a “flipped” duplicate of their behaviours in front of the mirror. This spatial relationship between the two bodies could potentially provide an intuitive visual reference for user interaction with virtual augmentations around the physical body while observing the reflected body and the augmentations in its surroundings. This was echoed by our formal evaluation results that 2PP target selection performance benefited from seeing the physical and reflected hands (MANUAL) and the targets on both sides of the mirror (DOUBLE) simultaneously while participants potentially benefited from being able to better locate the targets while using the synchrony between their physical and reflected hands as a moving spatial frame of reference. Similarly, users could also locate AR objects in the physical space more easily by first identifying their reflections in the mirror while using the mirror and their own bodies as references. For instance, participants in the visual search task were able to first identify the reflected virtual target in the mirror, find it in their surrounding physical space, and then select it, which was still faster than directly searching for it in the physical space. In relevant application scenarios, users could also directly remote-select the reflected target through the mirror. The smart mirror could further expand the FoV even when users are not looking at the mirror, while they would still be able to see the AR objects rendered on the smart mirror in their peripheral vision.

8.2 Extension: pushing the interaction through the mirror

By connecting the reflected space behind the mirror with the physical space in front of it using continuous tracking across the two spaces, the usable interactive space is expanded by more than twice. In reflected reality, users are able to use the space shared between their physical and reflected body as one continuous space, such as to transport virtual objects between them. In addition, they can also use the space around and behind their reflected body by directly interacting with objects located in that space using interaction techniques such as ray casting with controllers or "point and commit" with their hands [6]. As participants commented in the exploratory study, reflected reality is the only AR interface that affords such interaction by enabling input from 1PP in the reflected space.

Once users understand the extended interactive space, they can benefit from switching between temporarily using the space behind the mirror as a reflection or as an extension for the interaction task at hand. In the use case scenario, the user performed such mental switch interacting with the Penrose triangle while perceiving the reflected space first as reflection and later as extension. An interesting feedback from the exploratory evaluation, referring to the task of pushing the virtual picture into the reflection, suggested that the participants were expecting the object to follow the reflected direction of movement once it crossed the mirror, instead of keeping moving towards the same direction as in the physical space. Although both participants said that they quickly became used to it, future work could explore different forms of feedback to inform the user of an object crossing the boundary between the two spaces.

8.3 Smart Mirror: the temporal dimension

To fully grant the pervasive mirror reflections with AR interactivity, we included the smart mirror component into reflected reality to compensate the AR HMD. The smart mirror, like any ambient display, could remain available as long a it is left on. This feature better simulates ordinary mirrors which invite people to walk up to them and use them anytime, unlike AR HMDs which are only put on for specific interactions. This difference between the smart mirror and HMD opens up new possibilities for reflected reality interaction.

For instance, as demonstrated in the scenario, the smart mirror could be an ambient display for contextualised notifications or other information through rendering virtual objects registered in the reflected space, similar to the Magic Bench [35]. This potentially extends the temporal dimension of using reflected reality not to be limited by the time wearing the AR HMD. However, the connection established between the smart mirror and the HMD through shared motion tracking and spatial mapping enables users to intermittently use the HMD to modify the AR content persistent in the smart mirror, such as the example of hanging a virtual picture illustrated in the scenario. The smart mirror serves as an ambient AR display reflecting the space in front of it, and the HMD could be used for editing that space benefiting from its richer interaction affordances.

The capability of rendering AR content that persists without a HMD also enables shared AR experiences between different users, either synchronously or asynchronously. For instance, multiple users can take turns to walk up to the smart mirror to observe 3D content rendered in the reflected space and exchange their opinions. At anytime, one user could modify the 3D content by putting on an HMD, while the other users could see the augmented mirror reflection being updated, and provide feedback in real-time.

8.4 Focus+Context in reflected reality

Duplicating the bodies and perspectives of the user, together with extending the space for interaction, enables reflected reality users to use different dimensions of the spaces as focus and context interchangeably [5]. For instance, the scenario demonstrated how users could find objects in the physical space (paperclip) while using the reflected space as context, and use mirrored pairs of virtual objects in both spaces as context for each other (while observing the Penrose triangle). This was supported by the visual search task in the formal evaluation where participants were able to quickly find and select virtual targets in the physical space after identifying their reflections in the

[6] docs.microsoft.com/windows/mixed-reality/design/point-and-commit

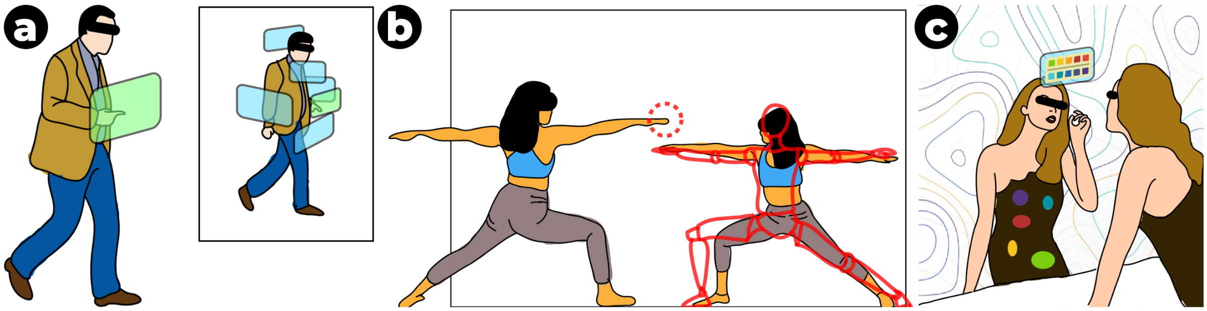

Fig. 14. Example applications supported by reflected reality: (a) Encouraging serendipitous interaction by rendering ambient information when users walk past mirrors; (b) Movement training benefiting from seeing different instructions on both sides of the mirror; (c) Modifying the appearances of the clothing and the reflected space for immersive fashion design.

mirror. Further, the wider FoV for rendering AR content in the mirror allows users to see more in AR as contextual information while they perform tasks in the physical space. This would be useful in situations where users try to place AR objects at specific locations in the physical space in front of the mirror or relative to their bodies, such as hanging the picture and putting the email into the paperclip from the scenario, which were only possible by using the reflected room and body as context for the AR interaction happening in the physical space in focus.

8.5 Summary

While the potential benefits of reflected reality go beyond what we list here, we have summarised the essential interaction affordances through the scenario, which was designed to showcase all combinations of the design space elements. We have demonstrated how AR interaction in the reflected space can benefit from the duplicated bodies and their perspectives, the extended interaction space across the mirror, Focus+Context during interaction, and the interaction affordances enabled by the smart mirror on the temporal dimension. Within the line of HCI research on augmented mirror interfaces, we posit our work as the next step in its evolution, granting a rich set of interaction affordances to the reflected space behind the mirror. Within the line of HCI research on AR interaction, our work opens up a new dimension as the first AR interface that enables users to interact directly with their reflections, with a virtual extension of the physical space, with a larger FoV, and with an alternative visual and mental perspective to perform input from.

8.6 Future work and applications

With its unique interaction affordances enabled by the combination of the smart mirror and the AR HMD, reflected reality has strong potential for applications in different areas. For instance, the use case scenario described in this paper illustrates a plausible picture of what mirrors of the future could look like in domestic and work environments as mixed reality user interfaces. By enabling an exocentric perspective and an FoV considerably larger than AR HMDs', reflected reality gives users more space for interaction, for potentially improved efficiency in performing daily interaction tasks in AR, such as those demonstrated in the scenario.

The pervasiveness of mirrors gives a rich set of opportunities for applications of reflected reality. For instance, when the presence of a mirror is detected by a reflected reality system, they can use the reflected space in the mirror to display information that encourages serendipitous interaction [39]. In addition, previous work in public display suggested that a mirror view could be used to attract users' attention for them to recognise themselves before engaging in further interaction [29]. Figure 14 (a) illustrates a scenario of an user walking past a large mirror while interacting with an AR widget through his headset. Upon recognising the mirror, the system uses the reflected space around the user's body to display widgets of applications that generated notifications previously ignored by the user. With a glance at the mirror, the user sees the widget of one application and is reminded of the content of the notification. By pulling the widget out of the reflected space, the user is able to directly interact with the application and finish the task associated with the notification.

Reflected reality can be implemented and adapted for many application areas where mirrors are prevalent. For instance, movement training usually involves mirrors for learners to observe and correct their performance. HCI works have already explore applications in this area featuring smart mirror interfaces to provide feedback to users with their body reflections as context [1, 50, 61–63]. Reflected reality opens new opportunities for movement training by enabling the physical space to be augmented with virtual objects as well as the reflected space in the mirror. This provides users with movement instructions and performance data visualisations in both 1PP and 2PP with likely benefits for training. For instance, Figure 14 (b) illustrates a yoga training application in reflected reality. The user sees an instructor avatar demonstrating a pose in the reflected space, and tries to perform the same pose by aligning their reflected body with the instructor. While trying to perform their full-body posture correctly by looking into the mirror, they also get instructions about more fine-grained movements from the 1PP in the physical space. For example, here she is instructed to put her hand at a specific position with a visual cue.

One of the most common use of mirrors in retail and in domestic spaces is for fashion. Figure 14 (c) illustrates a scenario where an user designs a dress in front of a mirror using reflected reality. While the mirror overlays excel at showing the outfit on their body, the interactions in the physical space in front of the user through the headset are better for precise manipulations. For example, in the figure, they choose colours and patterns from a palette widget from 1PP, and add them onto the dress on their reflected body through the mirror. The user can also modify the appearance of the reflected space to see the dress in different environments and lighting conditions.

8.7 Limitations

We designed the use case scenario to instantiate the design space. While we were able to demonstrate most of the important combinations of the dimensions and levels in the design space, we did not cover all the possible combinations, such as 2PP interaction performed while using the reflected space as an extension. We discussed the potentials for reflected reality interaction along those dimensions of the design space, along with novel interaction afforded potentially by other input modalities and in other scenarios in section 5.7. While the 2D information displayed by the smart mirror over the optical mirror reflection is limited by its technical capabilities, we discussed its uses for displaying contextual information as an aid to the HMD, and for enabling reflected reality interaction without the HMD. Future work could explore potential technical solutions for rendering 3D content on the smart mirror, to further enrich the reflected reality design space. While the exploratory study was designed mainly for instantiating the design space, it could serve as an inspiration for future works to conduct more comprehensive usability testings of implementations of reflected reality in different contexts with concrete tasks. While the formal evaluation study in the current work characterises the usability of basic hand interactions in reflected reality, future works could expand the evaluation to broader contexts, such as in combination with gaze [40], body [58], and in multi-user scenarios [17].

9 CONCLUSION

In this work, we contribute *reflected reality*, a new dimension for augmented reality enabled by the novel combination of an augmented smart mirror and an AR HMD with appropriate hardware and software configurations. Our work combines and extends the lines of HCI research on incorporating mirror reflections in interactive user experiences. Reflected reality grants new interaction affordances to the reflected space behind the mirror by connecting it with the physical space in front of the mirror. We introduced our design space around its three axes: Perspective, Frame of Reference, and Direction. Together, these dimensions cover important design factors for utilising the reflected mirror space for AR interaction. Through a use case scenario visualised with our proof-of-concept prototype, an exploratory user study, and a formal evaluation study quantitatively characterising interaction performances, we demonstrated how reflected reality benefits AR interaction by creating duplicated bodies and their input perspectives, extending interaction space across the boundary of the reflected space, optionally synchronising between both sides of the mirror, and expanding AR interaction along the temporal dimension with the smart mirror component. As the next step in the evolution of mirror-based interfaces, reflected reality transforms the mirror reflection into a full-scale AR space open for user perception and interaction. At the same time, reflected reality pioneers traditional HMD-based AR into a new dimension, enabling interaction with the augmented self from an exocentric perspective, and expanding the available physical space for AR interaction into the territory of mirror reflection. With our work, we hope to inspire future explorations on interaction design for mirror-based interfaces, and on utilising mirror reflections in AR.

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