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Blending On-Body and Mid-Air Interaction in Virtual Reality

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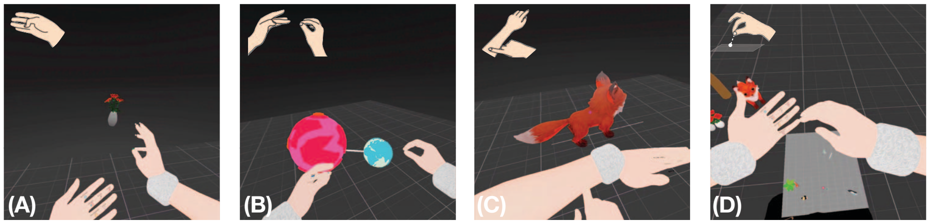

Figure 1: Sample interaction techniques based on BodyOn. (A) A user is scaling a vase towards a specific direction by performing thumb-on-finger gestures and mid-air movements. (B) A user is rotating a blue planet around and/or moving it towards a red planet by combining bimanual thumb-on-finger gestures with mid-air input. (C) Finger-on-arm gestures and mid-air input enable users to translate a fox with one degree of freedom. (D) Users can teleport to different locations by manipulating an on-body minimap display.

ABSTRACT

On-body interfaces, which leverage the human body's surface as an input or output platform, can provide new opportunities for designing VR interaction. However, it remains unclear how on-body interfaces can best support current VR systems that mainly rely on mid-air interaction. We propose BodyOn, a collection of six design patterns that leverage combined on-body and mid-air interfaces to achieve more effective 3D interaction. Specifically, a user may use thumb-on-finger gestures, finger-on-arm gestures, or on-body displays with mid-air input, including hand movement and orientation, to complete an interaction task. To test our design concepts, we implemented example interaction techniques based on BodyOn that can assist users in various 3D interaction tasks. We further conducted an expert evaluation using the techniques as probes to elicit immediate design issues that emerge from the novel combination of on-body and mid-air interaction. We provide insights that can inspire and inform the design of future 3D user interfaces.

Index Terms: Human-centered computing—Human Computer Interaction (HCI)—Interaction Paradigms—Virtual Reality;

1 INTRODUCTION

Virtual reality (VR) technologies, or immersive technologies in general, represent a significant paradigm shift from the traditional PC-based interaction by putting users "into" the digital content. Whereas a large number of VR techniques enable users to interact with content located within a virtual environment through mid-air input (like hand movement or orientation) [1, 41], interfaces that leverage users' *on-body spaces*—the virtual representation of the human body's surfaces—are often overlooked.

The on-body space offers new interaction possibilities for VR systems: it is always available [28,29], allows eyes-free targeting [26,53], and provides a supporting surface for input [25, 28]. However, the design space of how on-body interaction can be incorporated into current mid-air interaction workflows in VR systems is largely underexplored [8]. While on-body interfaces can be appealing, they cannot fully replace the current paradigm based on mid-air interaction. For instance, mid-air techniques are more appropriate than on-body ones to enable 3D translation and movement of objects in VR. Therefore, it is critical to explore the synergies across these input modalities to best leverage their strengths and overcome their limitations.

To explore this opportunity, we propose *BodyOn*, a design space consisting of six design patterns for integrating on-body interfaces into current mid-air interaction workflows in VR headsets (Figure 1). In contrast to previous work that considered the on-body space as a standalone input and output modality [5, 7, 22], BodyOn takes a unique perspective by combining both on-body and mid-air interfaces to expand the design space of VR interaction techniques. Within this design space, a user may use thumb-on-finger gestures, finger-on-arm gestures, or on-body display in combination with mid-air input, including hand movement and orientation, to accomplish various VR interaction tasks (see Figure 1 for examples).

We instantiate this design space through a set of example interaction techniques based on BodyOn to accomplish canonical interaction tasks in a 3D modelling system, including selection, manipulation, navigation, and system control (e.g., menu control and mode switching). These techniques served as probes to showcase possible designs with BodyOn, and allowed us to form a testbed to verify the feasibility and applicability of the high-level design concepts. We then conducted an expert evaluation to gather feedback about the implemented interaction techniques. The study allowed us to identify immediate design issues with the new combination of on-body and mid-air interactions. For example, we found that when users focus on manipulating objects in the mid-air space, they can ignore on-body visual feedback. We discuss the lessons learned from our experience regarding future systems that may benefit from BodyOn.

The main contributions of our work are:

- BodyOn: a collection of six design patterns for inspiring new 3D UI designs that combine on-body and mid-air interactions in immersive VR space.
- Example interaction techniques to explore the design space and showcase how to solve 3D interaction tasks at various complexity levels with BodyOn.
- Insights based on an expert evaluation for future systems that leverage both on-body and mid-air interactions.

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2 RELATED WORK

BodyOn enhances current mid-air interaction techniques in VR systems by incorporating on-body interaction.

2.1 Mid-Air Interaction

Mid-air interaction is the most common form of interaction in contemporary headset-based VR systems. It allows users to control and manipulate digital content in VR through mid-air gestures and movements, typically using game controllers or bare hands [14, 35, 49]. Previous research has identified mid-air interaction as being natural, straightforward, and particularly suitable for manipulating virtual contents in 3D space given its high degree-of-freedom input [36]. However, it has also long been criticized for being imprecise [4, 41], fatiguing [32], and for lacking tactile feedback [20].

To further improve the usability and increase the interaction vocabulary of mid-air interaction, researchers have explored low-effort approaches with indirect mapping of input (e.g., a relaxed arms-down position [12, 40]) and employed computational models (e.g., based on selection distribution [56]) to improve its accuracy. Others have leveraged the potential benefit provided by multi-modal input and have incorporated other modalities (such as eye gaze [57], smartphones, and tablets) into the interaction [11]. For example, *BISHARE* [59] investigated joint interaction paradigms between smartphones and AR headsets to enrich AR interaction experiences by distributing system input and virtual content across both platforms. Other recent research including *SymbiosisSketch* [3], *TabletInVR* [48], and *VRSketchIn* [16] contributed new design spaces using on-tablet input to assist mid-air input in sketching and modelling in VR. In this work, we focus on using on-body interfaces to enhance and augment mid-air bare-hand interaction in VR headsets.

2.2 On-Body Interaction

On-body interfaces leverage the human body as an input/output platform [8, 28, 29]. Compared with smartphones and tablets, previous studies have identified that on-body interfaces provide the following unique benefits: they are always available for interaction [28, 29], afford a higher sense of agency [9, 15], and enable more accurate eyes-free targeting [26, 53]. Additionally, they support additional haptic feedback [25, 28], which has the potential to enable more precise and less physical demanding input than mid-air input due to the direct physical contact with the user's own body [4, 30]. For these reasons, on-body interaction holds a lot of potential for supporting mid-air interaction in VR headsets. However, on-body interfaces usually lack direct support for providing 3D input.

Existing literature has proposed several on-body interaction techniques [23, 34, 44]. For example, *Armura* [28] explored a set of possible interactions like menu navigation, page-turning, and peephole display using hands and arms as projection surfaces. *PalmGesture* [52], *PalmType* [51], and *DigiTouch* [54] all considered the use of on-palm input for text entry and widget-based interaction in AR/VR headsets. *SkinWidget* [5] demonstrated on-forearm touch, drag, slide, and rotation gestures for interacting with an on-arm menu in VR. *BodyLoci* [22] and *Tap-Tap Menu* [7] further used tapping gestures to interact with menus and buttons located on the whole body in VR. *DigiGlo* [13] proposed palm surfaces as a display in VR. Body-referenced input (interfaces that are attached close to a user's body surface) has also been explored in VR [6, 38, 55].

More relevant to our work are interaction techniques that consider combining both on-body and mid-air interfaces. *BodyScape* [50] evaluated a technique that employs mid-air gestures for pointing and on-arm tapping for selection confirmation. This work opened up new opportunities for combining the two interaction modalities. *WatchSense* [46] leveraged smartwatch-based fingertip tracking to enable combined mid-air and touch interaction by using the thumb as a base for touch input and the index finger for mid-air input. Ens et al. [18] integrated mini-scale on-finger input (for example, on a ring device) with mid-air gestures to allow 3D content manipulation by varying the temporal relationship of the input.

In summary, existing research has shown great promise of on-body interfaces, but few works have demonstrated their use for supporting mid-air interactions. Our research takes these ideas further by exploring how on-body interfaces should be incorporated into the mid-air workflow.

3 BODYON

BodyOn is a collection of six design patterns that integrate on-body interfaces into current mid-air interaction workflows in VR headsets. In this section, we first present a design space that leverages on-body and mid-air interfaces as input and output modalities. We then identify design opportunities in the literature that motivate the design of BodyOn and detail the six design patterns which are templates of design that can be adopted to solve a multitude of interaction tasks.

3.1 Design Space

Both on-body and mid-air gestures can serve as modalities to capture user input or display output. We present a design space that connects on-body and mid-air interfaces in different input and output forms for interaction (see Figure 2 left).

The design space has two dimensions. One dimension is *input*: on-body, mid-air, and the combined on-body + mid-air information can all be used as input. In the scope of this research, on-body input leverages body contact information (on-body touch, gestures, or deformations [8]) as an input modality for interaction, while mid-air input employs mid-air gestures including hand translation, rotation, and relation as an input modality. The combination of on-body and mid-air input means that the interaction is a result of inputs from both modalities. For example, a user can achieve this by performing mid-air gestures with one hand and on-body gestures with the other hand for input. The other dimension of the design space is the *output*: both on-body and mid-air can be used as output. That is, virtual contents can be either attached to body surfaces or to the mid-air space as displayed output.

Based on the design space, we identify input → output mappings that combine on-body and mid-air interfaces, including On-Body → Mid-Air, Mid-Air → On-Body, and On-Body + Mid-Air → *Output* (on-body or mid-air). Additionally, we envision virtual content to be transferred between on-body and mid-air space for leveraging unique properties of the displays (*Output*: On-Body ⇌ Mid-Air). Because this work focuses on blending on-body and mid-air techniques, we exclude conditions where there is only one single input and output modality (i.e., On-Body → On-Body and Mid-Air → Mid-Air). We scrutinize the relevant mappings in the next section.

3.2 Synthesis of Prior Work and Design Opportunities

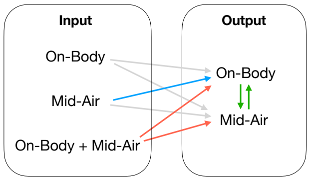
We have identified possible mappings between on-body and mid-air interfaces for input and output. We further explore new design opportunities by examining how existing research fits into our design space.

3.2.1 Manipulating Mid-Air Content with On-Body Input

For the On-Body → Mid-Air mapping, prior research has proposed techniques that leverage finger-on-palm gestures for text entry or application control (e.g., sliding fingers to increase the volume of an application) [51, 52, 54]. However, little work has employed on-body input for manipulating objects in 3D mid-air space. This is understandable if we consider the affordance of on-body input—body surfaces naturally afford 1D, 2D, but only limited 3D input based on their geometry and how they are positioned and stretched [10, 43]. Therefore, we deem existing applications that mainly use on-body input for 2D content manipulation appropriate and sufficient for this mapping.

3.2.2 Manipulating On-Body Content with Mid-Air Input

A few works have explored the Mid-Air → On-Body mapping [37]. For example, *Armura* [28] allows users to flip a page displayed on the



Mapping	Key Literature
On-Body → On-Body	*Armura* [28], *SkinWidget* [5], *Haptic Hand* [34], *Tap-Tap Menu* [7]
On-Body → Mid-Air	*PalmGesture* [52], *PalmType* [51], *DigiTouch* [54]
Mid-Air → Mid-Air	A common VR interaction paradigm [36]
Mid-Air → On-Body	*Armura* [28], *DigiGlo* [13], body-referenced input [37, 38, 55]
On-Body + Mid-Air → *Output*	*BodyScape* [50], *WatchSense* [46], Ring-based interaction [18]
Output: On-Body ⇌ Mid-Air	Not available

Figure 2: Design space and key literature summarization.

hand with swiping gestures. *DigiGlo* [13] enables users to interact with games displayed on their hands through various hand gestures in VR. Wrist-referenced interfaces [38, 55] allow users to interact with UIs displayed on or close to their wrist. While these works focus on using hands or arms as displays, we argue that body surfaces afford larger display areas if considering other body parts like the torso, legs, feet, etc. Different body parts can be designed to convey different semantic meanings of an interaction. Thus, one underexplored space is to use mid-air input to interact with virtual content displayed on body surfaces other than on hands and arms.

3.2.3 Combining On-Body and Mid-Air Input

Existing works have considered combining on-body and mid-air input for interaction (On-Body + Mid-Air → *Output*). *BodyScape* [50] uses one hand for mid-air pointing and the other hand performing on-arm tapping for selection confirmation. *WatchSense* [46] uses a thumb for on-hand touch (which creates a stable base) and an index finger for mid-air controls like zooming in/out an image. Ens et al. [18] use thumb-on-index finger tapping and swiping gestures to provide additional capabilities for mid-air input. While these works demonstrate the potential usefulness of combining on-body and mid-air input, there is still no cohesive view on how on-body and mid-air input should be combined, especially considering the bimanual input capability of hands [24]. Leveraging the feature that each hand can perform separate or combined on-body and mid-air actions, a user interface may create a richer set of interaction vocabularies to afford more complex interaction tasks in VR systems. Therefore, one design opportunity here is to scrutinize how on-body and mid-air input can be combined, considering the bimanual input property of hands.

3.2.4 Content Transfer Between On-Body and Mid-Air Space

Little research has explored content transfer between on-body and mid-air space (*Output*: On-Body ⇌ Mid-Air). However, mid-air and on-body spaces have unique display affordances. The mid-air space provides an extensive area for displaying 2D or 3D virtual content [19]. However, because virtual objects and user interfaces are anchored to the world space, unwanted occlusions may occur if users change their viewpoint (e.g., an element of interest is occluded by a wall [58]). In contrast, when a UI display is attached to the body surface, it follows the user's movement when travelling inside virtual environments and can be accessed once the user pays attention to it. For example, when a user is walking, the on-body displays attached to their wrists, belly, or feet will always be available for interactions when the user looks at them. Therefore, one design opportunity is to enable content transfer between the two displays to better leverage their strengths.

3.2.5 Summary

In sum, we conclude with three design opportunities. (1) On-Body + Mid-Air → *Output*: combining on-body and mid-air input for interaction, especially considering the bimanual input property for a rich set of interaction vocabularies, (2) Mid-Air → On-Body: extending the display of virtual contents to body parts other than arms and hands, and (3) *Output*: On-Body ⇌ Mid-Air: enabling content transfer between the two interfaces to better leverage their unique display properties.

3.3 Design Patterns

Based on the identified design opportunities, we propose BodyOn, a set of six design patterns that combine on-body (*OB*) and mid-air (*MA*) interfaces for interactions in VR headsets (see Figure 3). The design patterns leverage combined OB and MA input (**P1**-**P4**), MA input for OB content manipulation (**P5**), and content transfer between OB and MA space (**P6**).

3.3.1 Combining On-Body and Mid-Air Input

We envision that OB and MA input can be combined in various ways for interaction, especially considering the bimanual input property of hands. In this research, we restrict the input area of OB interfaces to hands and arms because they are more comfortable and socially acceptable by users across multiple poses [10, 27, 50].

Under this constraint, we identify two types of OB inputs that are suitable for combined OB and MA input: thumb-on-finger (*TOF*) input and finger-on-arm (*FOA*) input. TOF input leverages contact information between a thumb and other fingers on the same hand to issue an input. FOA input uses contact information between the fingers of one hand and the arm of the other hand to command input. Users can perform a diverse range of gestures including tapping, sliding, and drawing shapes, and information like contact locations, hardness, and gestures can be employed to construct input signals.

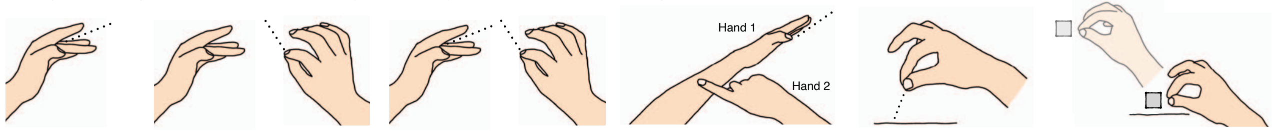
TOF input can be performed with one hand or both hands, and, concurrently, MA information of one or both hands can be leveraged for input. FOA input require the involvement of both hands, and the hand that does not perform FOA input can be used to provide MA input. These combinations result in the following four patterns.

Pattern 1 - Single Hand: MA + TOF. Users perform single hand TOF input and MA input together to interact with virtual objects. While previous research on TOF gestures mostly focused on gesture recognition [33, 45] or utilizing these gestures for interactions like text entry [54], our work emphasizes the incorporation of the TOF input into the MA input flow. In this case, MA information (i.e., hand position and/or orientation) is combined with TOF input to enable a richer set of interactions. For example, when manipulating an object with MA input, TOF input can provide another layer of control to adjust the object's movement speed.

Pattern 2 - Both Hands: MA (One Hand) + TOF. Users perform MA input with one hand and TOF input with the other hand or both hands. The pattern involves both hands, while only one hand's MA information (position and orientation) is used for input. The hand that issues MA input can work on a primary 3D interaction task, and the TOF input can act as background support for the primary task. For example, a user is drawing 3D curves with one hand in a virtual space, and the user can perform TOF input on the other hand to quickly change the drawing colours in an eyes-free manner without disturbing the workflow of the drawing hand.

Pattern 3 - Both Hands: MA (Both Hands) + TOF. Users carry out MA input with both hands and use TOF input on one or both of the hands. In this pattern, the MA information from both hands, including their locations, orientations, and relations, is used. Simultaneously, TOF input comes into play (performed by one or both hands) to uncover more complex interactions that are possible in 3D VR environ-

*** Acronyms summary: Mid-Air (MA), Thumb-On-Finger (TOF), Finger-On-Arm (FOA), and On-Body (OB)**



Pattern 1
Single Hand:
MA + TOF

Pattern 2
Both Hands:
MA (One Hand) + TOF

Pattern 3
Both Hands:
MA (Both Hands) + TOF

Pattern 4
Both Hands:
MA (Hand 1) + FOA (Hand 2)

Pattern 5
MA Input +
OB Output

Pattern 6
Content Transfer Between
MA and OB Space

Figure 3: BodyOn is a collection of six design patterns that combine on-body and mid-air interfaces for new VR interactions. **P1** leverages single-handed thumb-on-finger (TOF) input and mid-air input (i.e., translation and orientation) for user input. **P2** involves both hands and uses TOF input to support mid-air input performed by the primary hand. **P3** employs TOF to support mid-air input performed by both hands. **P4** uses finger-on-arm input with one hand on the other arm, while the latter is used for mid-air input at the same time. **P5** utilizes mid-air input for interacting with on-body displays. **P6** enables content transfer between on-body and mid-air space.

ments. The underlying concept is similar to many asymmetric bimanual techniques where one hand acts as a spatial reference and the other is used for manipulation [24]. For example, using the MA information from both hands may allow users to rotate an object (holding by one hand) around a point (attached to the other hand) or move an object towards a particular point. TOF input can act as a mode switching trigger to allow the transformation to happen between those two possibilities.

Pattern 4 - Both Hands: MA (Hand 1) + FOA (Hand 2). Users perform FOA input with one hand on the other arm, while the latter is used for MA input at the same time. In this pattern, the arm that performs MA input also serves as a place for FOA input. This is a novel approach as previous works that use FOA gestures use them as a sole input modality [5, 39]. As an example of where this pattern would be useful, users may want to translate a 3D cursor [58] to select objects with different depths by sliding fingers on the arm and pointing in the target direction.

3.3.2 Manipulating On-Body Content with Mid-Air Input

While previous works have explored OB displays mainly on hands and arms, we want to expand the design space to consider content display on other body parts such as the torso and feet. Therefore, we summarize the following pattern.

Pattern 5 - MA Input + OB Display. Users use MA input techniques (like Raycasting, remote virtual hand, or distant triggering) to interact with OB displays. While the appropriate areas for direct OB input are restricted to hands and arms, OB displays can be extended to other body parts which can benefit users with their unique features (e.g., inherently following the user's movement). Thus, an alternative solution can be to use MA input to interact with such OB interfaces remotely. For example, users can point and select a virtual OB widget and move them across different body parts. They can also trigger certain actions remotely by putting one hand close to OB widgets.

3.3.3 Content Transfer Between On-Body and Mid-Air Space

We envision that enabling content transfer between OB and MA space can better leverage the display properties of the two interfaces. Therefore, we derive the following pattern.

Pattern 6 - Content Transfer. Users can transfer objects between MA and OB space. For example, users may want to store a model inside a 3D virtual space as a prefab for later use. In this case, they can transfer the object from the MA space to their OB space and put it back to the MA space at a different location.

4 EXAMPLE INTERACTION TECHNIQUES BASED ON BODYON

To examine the *feasibility* and *applicability* of the design patterns, we developed a set of example interaction techniques based on BodyOn to solve various VR interaction tasks in a 3D modelling system[1]. Our goal was to use these interaction techniques as probes to test the high-level design concepts from BodyOn. By developing the techniques, our intention was to sketch "what is possible" with the new design patterns and map out possible design boundaries. These example techniques further allowed us to conduct an expert evaluation to elicit immediate design issues with the new combination of on-body and mid-air interactions.

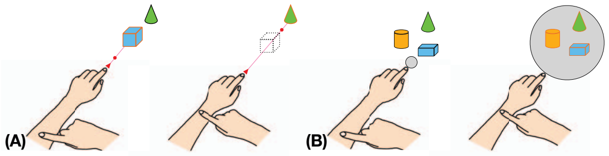


Figure 4: A user can select an occluded target (A) or a group of targets (B) with finger-on-arm gestures and mid-air pointing.

For demonstration purposes, we used 3D modelling as a testbed because it involves canonical interactions (select, manipulate, travel, and system control [36]) with various complexities in 3D UI design. For each interaction task, we considered how on-body interfaces can enhance the current form of mid-air interaction or achieve additional functionalities by leveraging BodyOn. Table 1 provides an overview of the techniques and how they fit into the design patterns. Please also refer to our supplementary video for technique demonstrations.

4.1 Selection

Object selection is a fundamental task in interactive VR systems [2, 36]. Our interaction techniques based on BodyOn enable single object selection, occluded object selection, and group selection.

4.1.1 Simple Raycasting Selection

A user can select a target with Raycasting. When the pointer is "on" the object, the object will flicker to indicate that it is available for selection. The user can use the same mechanism to select objects attached to the on-body space (**P5**).

4.1.2 Occluded Target Selection

We developed a BodyOn-based occluded target selection technique inspired by *AlphaCursor* [58]. A user can control a movable cursor on the virtual ray attached to the index finger of their non-dominant hand (NDH) with finger-on-arm sliding gestures performed by their dominant hand (DH) (**P4**) to reveal occluded objects as the cursor goes deeper into the environment (see Figure 4A). The object is selected if a pinch gesture is performed with the DH. The object flickers once the selection ray hits it and gleams golden colour once selected.

4.1.3 Group Selection

A user can select a group of objects by controlling a resizable cursor attached to the index finger of their NDH. As shown in Figure 4B, the

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[1] Open source: `https://github.com/Davin-Yu/BodyOn-ISMAR22`

Table 1: A summary of the implemented interaction techniques and how they fit into the design patterns. Acronyms: TOF (thumb-on-finger), OB (on-body), FOA (finger-on-arm), and MA (mid-air).

Design Patterns	**Implemented Interaction Techniques**
P1 - Single Hand: MA + TOF	Simple object manipulation, adjustable CD ratio
P2 - Both Hands: MA (One Hand) + TOF	Stroking, coloring, menu control, object creation and removal
P3 - Both Hands: MA (Both Hands) + TOF	Plane, ray, and point techniques
P4 - Both Hands: MA (Hand 1) + FOA (Hand 2)	Occluded target selection, group selection, 1 DOF transformation, teleportation
P5 - MA Input + OB Output	On-body object selection, travel through minimap
P6 - Content Transfer	Object storage and retrieval

user can make the cursor larger or smaller by sliding the DH index finger on the arm of the NDH (**P4**). The selection is triggered once a pinch gesture is performed with the DH, and all the flickering objects inside the cursor are selected.

4.2 Manipulation

Object manipulation tasks commonly include translation, rotation, and scaling of objects [36,41]. Other tasks in relevant applications (e.g., Google Blocks and Tilt Brush) include stroking, colouring, object creation or removal, and object storage or retrieval.

4.2.1 Simple Object Manipulation

A common way of manipulating a selected object is to move or rotate the DH by holding the index finger pinch gesture. The object then follows the hand movement and rotation with 1:1 control-display mapping (CD Ratio = 1), as if the object is grabbed by the DH. A user can manipulate an on-body object in the same way (**P5**). Users hear a click sound once they select an object, and the facets of the selected object then start blinking.

Alternatively, a user can pinch their middle finger for object translation, pinch their ring finger for object rotation, and pinch their pinky finger for object scaling (**P1**) (see Figure 5). The additional three functionalities isolate the 6 degrees-of-freedom (DOF) virtual hand manipulation to 3 DOF for translation, rotation, and scaling. It does not require normal operations of going through multiple stages like using a DOF-separation widget, which may slow down the performance [31]. The quick access may give more control (object scaling) and precision (by separating the DOF [42]) for manipulation tasks.

4.2.2 Precise Object Manipulation

The techniques also enable precise object manipulation.

- *Adjustable CD Ratio*. When sliding the thumb from the fingertip to the root (**P1**), the control display mapping will change for each transformation. The CD Ratio changes to 2 when the thumb is on the second segment of the finger and changes to 1/3 when the thumb is on the third segment of the finger. This type of control may allow both precise (with a higher CD Ratio) and rapid (with a lower CD Ratio) manipulation [21]. Color indicators at fingertips turn to green, heavy green, or light green from their original state (gray) if normal, slow, or fast manipulations are enabled (see Figure 5B-E).

- *One DOF translation*. A user slides the DH index finger on the arm of the NDH (**P4**) to control a target moving along a line, which is defined by the pointing direction of the NDH (see Figure 6A). By isolating the movement to 1 DOF, the user may have more precise control over the manipulated target [41].

- *Plane, Ray, and Point* [31]. This technique uses shapes including planes, rays, and points to constrain object movement with multiple hand gestures [31] . Our method leverages the combination of on-body and mid-air bimanual input to achieve those functions (see Figure 6B-E). A user uses the NDH thumb to select the Plane, Ray, or Point technique with icons displayed on the NDH middle finger. A shape (plane, ray, or point) is generated once an index finger pinch is detected on DH, and the position and orientation of both hands are then used as references for the techniques (**P3**). The user may move the DH to rotate the selected object around a point, around a line, or along a plane. Alternatively, the user can quickly switch between different techniques by tapping their NDH thumb on the middle finger. If a middle finger pinch is detected when using the Point technique, the selected object moves towards the point rather than rotates around it. The design demonstrates that BodyOn allows more complex object control via both mid-air and on-body interfaces. Importantly, the menus displayed on-body make the functions fully discoverable and do not require remembering new gestures.

4.2.3 Stroking and Coloring

A user can produce a line stroke by holding DH index finger pinch. Meanwhile, the user can quickly access a colour palette displayed on NDH fingers and switch between different stroking colours with thumb-on-finger gestures (**P2**) (see Figure 7A). In this case, switching the colour may not disrupt the main workflow of the DH. A similar process can be followed to recolour an object.

4.2.4 Object Creation and Removal

A user can create an object (sphere, cube, cone, or cylinder) at the location of the DH by selecting a target shape icon on the NDH and pinching the DH index finger (**P2**) (see Figure 7B). The user can also use the DH index finger pinch to remove an object.

4.2.5 Object Storage and Retrieval

One interaction technique uses the on-body space as a container for storing and retrieving prefabs (**P6**). As shown in Figure 7C, a user can put a group of objects close to a pocket of the virtual avatar and release the DH index finger pinch to put them “into” the pocket. The saved prefab (on feet) can then be retrieved via Raycasting (**P5**).

4.3 Navigation

Teleportation and on-body minimap can be used for navigation.

4.3.1 Teleportation

A user can travel to a target location by teleportation with a parabolic curve. The initial curve has a take-off angle of 45°, a horizontal speed of 2m/s, with a vertical gravity acceleration. The user can perform a sliding gesture on the arm of the NDH (**P4**) to adjust the horizontal speed to maximize or minimize the furthest distance the user can travel through the teleportation technique.

4.3.2 Travel Through Minimap

A minimap [47] will pop up if a user puts the DH close to their abdomen. The minimap travel is triggered when the user moves the DH above the destination and performs a mid-air pinch gesture. The minimap can be closed if a user puts the DH close to their abdomen again. The manipulation of the on-body minimap relies on mid-air input for on-body displays (**P5**).

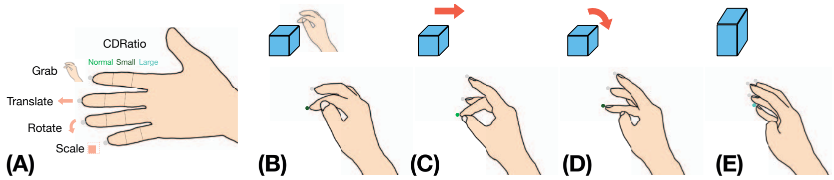

Figure 5: A user can manipulate an object using grabbing (B), translating (C), rotating (D), and scaling (E) by tapping the thumb on the index, middle, ring, and pinky fingers. The user can further adjust the movement/rotation speed (CD Ratio) to normal, slow, and fast by tapping on the first, second, and third segments of the finger.

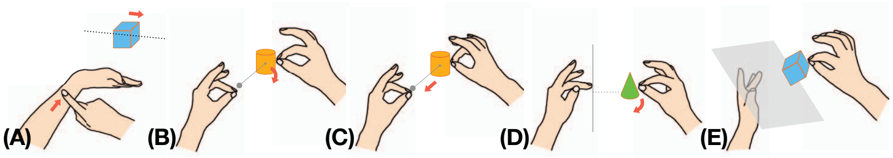

Figure 6: A user can translate an object in one DOF to enable more precise control by pointing at a movement direction through NDH and performing finger-on-arm gestures with DH (A). By combining various bimanual thumb-on-finger gestures and mid-air motions, the user can move an object around a point (B), towards a point (C), around a line (D), and along a plane (E).

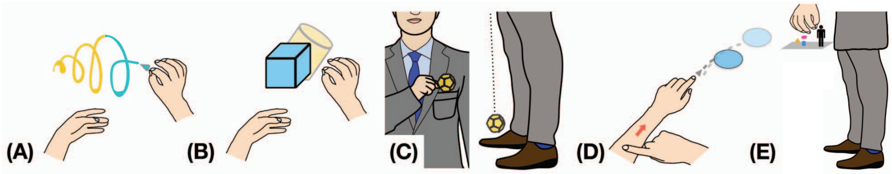

Figure 7: A user can use DH to draw lines with different colours (A) and create various shapes (B) by performing thumb-on-finger gestures on the NDH without disrupting the main workflow in the DH. The user can also store a group of objects by putting them into the pocket and later retrieving them from the feet (C). Moreover, the user can adjust the target destination of teleportation through finger-on-arm gestures (D) and travel to different locations by manipulating an on-body minimap (E).

4.4 System Control

We use the menu structure to navigate between the aforementioned functionalities or modes. The menu items are selected when the NDH thumb is tapped on the corresponding icon located on NDH fingers (**P2**). A user can quickly switch between different system functions without disturbing the main workflow. Furthermore, the eyes-free capability offered by on-body input may allow expert users to access different modes without looking at the icons.

4.5 Implementation

The interaction techniques based on BodyOn were developed with an Oculus Quest 2 headset (1832 × 1920 pixel resolution per eye). Hand tracking is enabled by its inside-out cameras, and the hand keypoints data are streamed from the OVR Plugin version 1.55.1. The software was developed using C# in Unity (version: 2020.1.17f1).

The arm and leg postures were approximated with two bone inverse kinematics (IK) constraints in the Animation Rigging package (version: 0.3.4). The feet would not go through a virtual floor, and the animated character's body rotation was constantly linearly interpolated to the horizontal orientation of the users' eyes.

The current vision-based hand-tracking in the headset still has limited tracking accuracy. They can suffer from occlusion and noise (e.g., lighting conditions), which may lead to inaccurate results when users' hands move around. Therefore, we implemented the thumb-on-finger and finger-on-arm gestures with the following compensations in our program to make the techniques more robust.

A thumb-on-finger gesture is detected once the distance between the thumb tip and other fingers' bones is smaller than 0.02m for index fingers or 0.03m for the middle, ring, and pinky fingers (as we found the tracking to be more accurate on index fingers). We determined the area of touch by calculating the distance from the thumb tip to the joints (proximal interphalangeal joints, intermediate interphalangeal joints, and distal interphalangeal joints) and the tips of each finger. We further increased the robustness of menu selection by picking up the closest menu icon to the thumb tip once the thumb-on-finger gestures are observed. When the hand movement exceeds a threshold (0.002m displacement and 0.5° rotation in 25 frames), the thumb tip is "locked" onto the finger to prevent unexpected clicking during the movement.

Similarly, a finger-on-arm gesture is detected once the distance between the index fingertip and forearm is smaller than 0.05m. The touch location is determined by calculating the distance between the index fingertip to the elbow and wrist.

5 EXPERT EVALUATION

Our interaction techniques represent different design possibilities based on the six design patterns of BodyOn. Therefore, the primary goal of our evaluation is not to fully validate the design space, but instead to use the techniques as probes to elicit immediate design issues with the novel combination of on-body and mid-air interactions.

5.1 Participants and Apparatus

Six experts, including one woman and five men, aged between 26 and 36, were recruited. All of them frequently use desktop-based 3D modelling software like Blender, Maya, AutoCAD, and Fusion 360 or game development applications such as Unity and Unreal. Three reported using VR/AR devices 3-5 times per week, while one reported using these devices almost every day. We hoped that domain experts would give us more insightful feedback on the interaction techniques and tools as they've already had previous experiences dealing with similar software (like modelling tools on PC). They were compensated $20 for participating in the study.

The study was conducted in a 3m × 4m tracking space. An Oculus Quest 2 headset, which is a standalone VR headset, was used in the study. The user's view was streamed to a laptop through Wi-Fi for observation and instruction.

5.2 Procedure

The walkthrough experience took about 60 minutes for each expert and consisted of the following three phases.

5.2.1 Welcome and Briefing (10 minutes)

The experts first filled in a consent form and a demographics questionnaire. We then introduced them to the purpose of the walkthrough, the overview of the six design patterns, and the interaction types that the techniques support (selection, manipulation, navigation, and system control).

5.2.2 Guided and Free-Form Exploration (30 minutes)

During the walkthrough experience, the experts were guided through all the techniques that corresponded to the six design patterns and were asked to complete specific tasks like constructing a door on its frame and rotating it around (detailed in the supplementary material). After completing all the required tasks, they were asked to perform free-from exploration while providing their thoughts on the interaction.

5.2.3 Interview (20 minutes)

After the exploration, we conducted a semi-structured interview with the experts where we asked them to (i) illustrate the advantages and disadvantages of the techniques over previous tools they had used in desktop software and VR applications; (ii) give their overall impression about the usability and learnability of the interaction techniques; (iii) describe what they liked and disliked; (iv) provide opinions on how we should further improve the techniques; (v) any other comments about the techniques or patterns that they had not covered.

5.3 Results

Overall, the experts (*E* in short) enjoyed the walkthrough experience and were positive about the combination of on-body and mid-air interaction. For example, *E1* commented "*The interactions are really intuitive, and the concepts behind the system are amazing!*" By combining on-body and mid-air interfaces, the system certainly brought "*a lot of new functionalities*" (*E2*, *E3*, and *E6*) as compared to existing software.

Using both on-body and mid-air gestures as input, users found many clever and helpful features were enabled. For example, the manipulation techniques of changing CD Ratio and isolating transformation enabled by single hand thumb-on-finger and mid-air gestures (**P1**) were mentioned to allow "*more accurate manipulation*" (*E6*) and could "*speed up the transformation for a large room*" (*E1*). experts also noticed that the gestures and techniques were "*easy to learn*" and they could control an object or switch between different modes with on-body gestures without looking at their hands or arms (eyes-free input). All experts particularly liked **P4**, with which they performed mid-air gestures with one hand and finger-on-arm gestures with the other hand to achieve operations like occluded object selection. For example, *E1* said that "sliding on arms was not tiring." *E2* mentioned that "*it enables a lot more functions and is less fatiguing (than mid-air input alone).*"

Several interesting comments pointed out potential issues with the current implementation of combined on-body and mid-air input. One main issue was related to how the feedback of on-body input should be displayed. *E3* noticed that it was hard to perceive the visual feedback provided on-body while focusing on the mid-air input. While using thumb-on-finger gestures to change CD Ratio, *E3* commented that "*because the (visual) feedback is on fingertips, when I am focusing on an object, I cannot see the feedback.*" Similarly, when performing mid-air tasks with one hand and on-body gestures with the other hand as support (**P2**), *E3* felt that when focusing on the mid-air input (e.g., painting) the current visual feedback provided on the non-dominant hand (which might be moved outside of the user's view) was not enough. *E3* mentioned that "*I need to see the feedback (of which mode the system is in).*" These comments resonated with the experience of some experts like *E6* who encountered unintentional misclicks from the thumb-on-finger input with the supporting hand (maybe due to system recognition error) and got confused about the unexpected mode switching event through the on-body input. *E6*, therefore, suggested that "*it would be better to sometimes detach the control panel on the body surface and put it in mid-air or disable it (to avoid misclicks).*"

In addition, the users also had various opinions on the input regions of thumb-to-finger gestures. While *E1* and *E5* found no problem performing all the gestures, others felt uncomfortable holding the thumb on the root of other fingers. Therefore, *E2* and *E3* suggested using thumb sliding and holding gestures only on the index and middle fingers, and *E3* further recommended using the pinky finger as a display rather than as an input region.

Another interesting finding from our observation is that although mid-air and on-body information is leveraged by the design patterns at the same time, users may not perform the mid-air and on-body input simultaneously. For example, while a user is performing mid-air pointing, finger-on-arm sliding often happens after the user has already pointed at the desired direction (e.g., for one DOF translation).

Regarding interaction techniques that allowed mid-air gestures to interact with on-body displays, all the users liked the minimap attached to the abdomen. They said that, for example, "*taking out a minimap from my body is cool.*" (*E1*) and described minimap as "*my favourite feature*" (*E4*). *E6* mentioned that it provided "*a nice top-down view (of the virtual environment)*". Users also found on-body and mid-air content transfer (**P6**) to be helpful and "*is the shortcut for copy and paste*" (*E2*). However, the placement of the on-body visualization may need to be carefully considered. *E5* mentioned that the minimap was placed "*too close to the body*". To retrieve an object from the foot, *E3* mentioned that "*I have to bend my body (to see the objects on my foot).*"

6 DISCUSSION

This paper introduces BodyOn, a collection of six design patterns that leverage both on-body and mid-air interfaces to achieve better interactions in VR. The patterns were designed for (1) combining on-body and mid-air input, especially considering the bimanual input property (2) extending the display area of virtual contents to body parts other than arms and hands, and (3) enabling content transfer between on-body and mid-air space. We ground our design concepts on a set of example interaction techniques to solve tasks at various complexities in a 3D modelling system. We further use these techniques as probes to elicit immediate design issues with the novel combination of on-body and mid-air interfaces in an expert evaluation study. In this section, we reflect on the lessons learned from our experience, and discuss limitations and future work.

6.1 Combining On-Body and Mid-Air Interaction

By instantiating the high-level design concepts through the interaction techniques, we confirm that BodyOn can provide versatile interaction vocabularies to support the current VR workflow based on mid-air interaction. On-body interfaces can provide quick controls to adjust the control-display ratio and isolate transformation with a simple combination of single-handed thumb-on-finger clicks/swipes and mid-air movements (**P1**). They also offer quick access to different tools with thumb-to-finger gestures as background support (**P2**). More complex interactions can be enabled by leveraging the mid-air relationship between two hands and combining it with thumb-on-finger input

(**P3**). Mid-air gestures can also be combined with 1D/2D sliding input on the arms to achieve additional useful and effective functions like selecting an occluded object (**P4**). Furthermore, using mid-air input to interact with on-body displays (**P5**) and transferring contents between mid-air and on-body space (**P6**) leverage the unique property of on-body display to make the content/information accessible while a user is moving inside virtual environments. The virtual menus displayed on body surfaces also make the interaction discoverable.

Our expert evaluation has demonstrated a great potential of combining on-body and mid-air interfaces. It showed that the interactions based on BodyOn could be quickly integrated into the mid-air interaction-based workflow and support the desired functionalities. The expert evaluation study also points out valuable lessons (*L*s) to further improve the designs.

6.1.1 Cognitive Bandwidth of On-Body and Mid-Air Interfaces

While BodyOn leverages on-body and mid-air input information simultaneously for interaction, users seem to have limited cognitive bandwidth in processing the information of two interfaces at the same time. For example, users were found to tend to perform finger-on-arm input after the hand that performed mid-air input has already pointed in the desired direction. Designers may need to *consider the additional cognitive load when combining these two interfaces and allow users to perform the actions sequentially (L1)*.

Furthermore, when users were focusing on manipulating objects located in the mid-air space, it was sometimes difficult for them to notice on-body visual feedback, such as small indicators on a fingertip or highlighted icons on a hand. The later issue may result in user confusion with the unintentional misclicks caused by on-body input because the input feedback is not perceived by the user. Therefore, it is essential to *present the feedback of on-body input within users' attention regions (L2)*. For example, it can be beneficial to provide a flashing icon on HUD or distinguished sound feedback when on-body input is detected to avoid user confusion. Such solutions aim to communicate the on-body input event that is being triggered while may introduce an additional cognitive burden in practical use.

Additionally, because unwanted on-body events can be caused by touching a trigger unintentionally when users are interacting with objects in the mid-air space, we recommend *providing a centralized button/gesture to switch on-body interfaces on and off as needed (L3)*. Another potential strategy is to implicitly determine users' current intention and determine whether an on-body click/touch should trigger a new event to mitigate the effect of misclicks [57]. For example, a designer can check the direction of gaze (on either body surfaces or mid-air interfaces) as an indicator of whether the user intends to perform on-body input. While these approaches may automatically filter out a large number of unintentional clicks, they can induce false-positive classifications (i.e., misclassifying a user's true intention).

6.1.2 On-Body Input and Output Location

Because previous research suggests that restricting the input area of on-body interfaces to hands and arms can be more comfortable and socially acceptable by users [10,27,50], we chose to employ thumb-to-finger and finger-to-arm gestures for on-body input. While all experts liked finger-to-arm gestures, we found it would have been beneficial to *enable thumb-to-finger input region customization (L4)*, because users have different preferences for the thumb-to-finger input regions. It will be useful to consider results from previous research by constraining the touching area to the first and second segments of the index and middle fingers to satisfy a larger population [33]. It may be further helpful to allow users to customize their own comfort regions and assign different functionalities on different finger segments by themselves (like personalizing their input control on a game controller).

Placing user interfaces on body surfaces like torso and feet can utilize previously unused on-body space for virtual content display. Interfaces presented on different body parts may convey different semantic meanings of interaction (e.g., putting a virtual object close to the heart means saving the object) and offer different viewing perspectives (e.g., top-down view of an on-body minimap attached close to the abdomen). Through the evaluation, we learned that *the location of on-body displays still needs to be carefully designed (L5)*. Due to the weight of current head-mounted displays, placing an object at locations that require users to heavily bend their body/neck (e.g., close to the chest) can induce discomfort.

6.2 Applications

BodyOn encompasses high-level design concepts that integrate on-body and mid-air interfaces. We envision the design patterns to be generalizable to other interactive applications in addition to 3D modelling. For example, in the emerging field of immersive analytics [17, 23], where users apply immersive technologies for data understanding and sense-making, new interactions are required for more challenging task scenarios like data manipulation and transformation. In addition, designers should have more choices to map out more complex interactions with the vocabularies enabled by BodyOn. Moreover, BodyOn can also inspire more fruitful interaction experiences in VR games. We also envision the design concepts of BodyOn to be adaptable to other displays like AR if carefully considering the affordance of the platform.

6.3 Limitations and Future Work

While the results of our study are encouraging, we have also identified several limitations regarding our current design and evaluation for future work. Our prototype was based on visual trackers from the headset (to make the system self-contained), and the tracking was not always accurate. Thus, the experts needed to adjust their postures periodically (e.g., rotating their hands or moving the hands back to the tracking area) to let the system recognize their postures, which might have affected their interaction experiences. Furthermore, the virtual character's body posture was approximated by inverse kinematics, and the torso and foot postures were not accurately captured. There are some more interesting design opportunities if the virtual character could follow the movement of users' feet and legs. Therefore, future work can incorporate tracking technologies with higher precision to explore these opportunities.

We also acknowledge the importance of quantitatively evaluating the techniques' performance in terms of, for example, user completion time and learning time. However, we did not conduct such studies because our designs were not implemented on a highly-accurate motion capture system (e.g., OptiTrack). Performing quantitative performance evaluation on our current prototype may introduce noises from the tracking system, thus producing misleading results. Therefore, we pursued a qualitative expert evaluation where our goal was to help elicit immediate design issues regarding the new combination of on-body and mid-air interfaces. We would like to include a quantitative evaluation of a more accurate system in a future study.

7 CONCLUSION

We present BodyOn, a collection of six design patterns that leverage both on-body and mid-air interfaces collaboratively for better VR interactions. Interactive techniques based on BodyOn were developed to showcase the possible designs with the patterns. We found that techniques based on BodyOn could provide flexible control, offer quick access to different tools, and bring additional useful and effective functions. They were easy to learn and could be quickly integrated into the mid-air interaction workflow. Our study also revealed some issues with our current implementation, such as users ignoring on-body visual feedback when focusing on mid-air tasks. Finally, we discussed the lessons learned from the implementation and evaluation, which can inform the design of future systems that blend both on-body and mid-air interactions. We envision BodyOn inspiring new interactions in a multitude 3D interaction scenarios in the future.

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