RemapVR: An Immersive Authoring Tool for Rapid Prototyping of Remapped Interaction in VR

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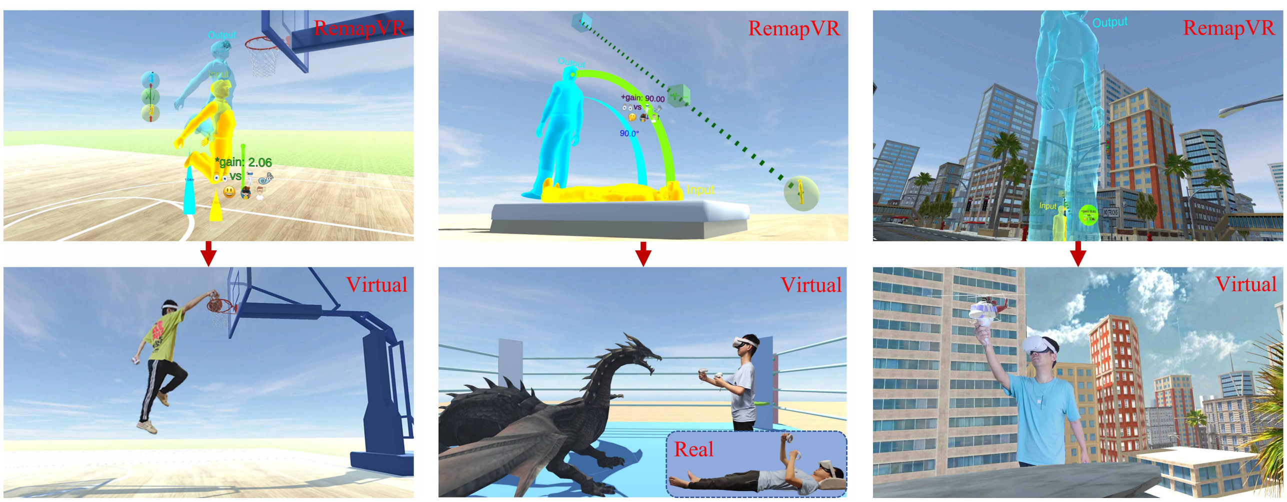

(a) High jump repositioning

(b) Upright redirection

(c) Whole body resizing

Figure 1: Remappings built by RemapVR. The first row shows the visualized remappings authored by the user, and the second row shows these remapping functions (from left to right: increasing the height of the high jump so that the user can easily dunk, making the lying user experience fighting monsters while he/she stands, enlarging the user's body to become a giant)

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Abstract

Remapping techniques in VR such as repositioning, redirection, and resizing have been extensively studied. Still, interaction designers rarely have the opportunity to use them due to high technical and knowledge barriers. In the paper, we extract common features of

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24 existing remapping techniques and develop a high-fidelity immersive authoring tool, namely RemapVR, for rapidly building and experiencing prototypes of remapped space properties in VR that are unperceivable or acceptable to users. RemapVR provides designers with a series of functions for editing remappings and visualizing spatial property changes, mapping relationships between real and virtual worlds, sensory conflicts, etc. Designers can quickly build existing remappings via templates, and author new remappings by interactively recording spatial relations between input trajectory in real world and output trajectory in virtual world. User studies showed that the designs of RemapVR can effectively improve designers' authoring experience and efficiency, and support designers to author remapping prototypes that meet scene requirements and provide good user experience.

CCS Concepts

• **Human-centered computing → Virtual reality**; *User interface design*; HCI design and evaluation methods.

Keywords

Immersive Authoring, Prototyping Tool, Remapped Interaction, Sensory Conflict

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1 Introduction

Through visual manipulation, remapping techniques (e.g., repositioning, redirection, and resizing) that decouple one-to-one spatial property mapping (e.g., translation, rotation, and scale) between real and virtual objects have gained significant attention in VR research [35]. They serve in a wide range of VR scenarios to fulfill specific functions, extend body capabilities, and create immersive illusions. For example, haptic repositioning allows a single physical object to act as a proxy for multiple virtual objects [5, 13], walking redirection helps avoid physical obstacles [45, 53], and giant resizing [1] enhances locomotion abilities. The key to designing remapping is carefully setting the gains (i.e., the mapping relationship of virtual-real spatial properties) [31]. However, designers face significant authoring challenges in effectively integrating remapping techniques into VR applications. First, designers encounter technical challenges, as they often struggle to quickly program, deploy, and experience the remapping prototypes they design. Second, there is the challenge of knowledge richness—designers may lack a comprehensive and deep understanding of the various types, functions, and conditions of remappings. Finally, there is the challenge of gain's iteration rationality—designers must strive to meet functional requirements while ensuring various user experiential factors, such as minimizing sensory conflicts, physical exertion, and risks of collision or falling, are adequately safeguarded. In practice, these barriers often hinder designers from adopting the remapping methods in actual VR applications, missing the opportunities to promote VR applications embedded with remapped interactions.

Recent immersive authoring tools in VR/AR show their potential in supporting designers without programming background to quickly iterate and validate design ideas and interaction concepts in a "what you see is what you get" (WYSIWYG) development environment [10, 11]. They are efficient for high-fidelity prototyping and have been widely exploited in various circumstances such as gesture interaction [65], tangible interaction [72], smart object interaction [69], etc. However, existing immersive authoring tools lack support for creating remapped interactions. Furthermore, their authoring approaches only offer solutions for addressing the technical challenges of remapping methods, leaving the issues of knowledge and setting rationality unresolved. Specifically, unlike the creation of other interactive content, remapped interaction introduces a unique problem of sensory conflicts, significantly complicating the challenge of setting rationality. As a result, summarizing the standard rules for remapping, enabling rapid prototyping in VR with clear visual indicators of the remapping methods and their sensory conflict effects would support efficiently iterating and validating remapped interactions and even composing new remappings, and broaden accessibility for designers with limited domain knowledge or programming skills, fostering inclusivity in the research area.

To this end, we propose RemapVR, an immersive authoring tool for designers as a first attempt to facilitate the rapid prototyping, iterating, and validating of remapped interactions in VR. RemapVR takes an approach of embodied demonstration of the correspondence of virtual-real spatial property changes with proper visual guidance and indicators to help designers better understand the various remapping techniques and weigh the experiential factors in determining reasonable gain, which is the key to alleviating the burden of prototyping remapped interactions on designers. To overcome the knowledge and technical challenges on designers, RemapVR is built upon a foundation of 24 existing remapping techniques from literature. Based on their common features of the remapping gains between input in real world and output in virtual world, RemapVR provides a unified framework to describe remapping configurations especially the gains from the various remapping examples, which not only help designers understand the concepts and methods of the remappings in a more structured way, but also laid the foundation for technical feasible to realize the prototyping tool. On the one hand, the derived templates based on the summary help designers accelerate the construction of existing remappings; on the other hand, the constructed design space based on the summary empowers designers with the ability to create new remappings. RemapVR provides a multi-branch authoring procedure and a series of visualization strategies of the spatial property changes, mapping relationship, and sensory conflict, aiding designers in solving setting challenges of weighing experiential factors. Through the input-output event-driven workflow of embodied demonstrating the physical and virtual corresponding trajectory in Editing Mode and experiencing/checking the remapping process in Experiencing Mode, designers can efficiently add, iterate, and validate the gain and interaction of remapping from scratch.

We conducted a user study to validate the design and evaluate the effectiveness of RemapVR. The experiment was divided into two parts. By letting designers complete more open propositions and customize new remappings, the first part evaluated the effectiveness of the multi-branch authoring procedure for helping designers to identify and solve various design challenges; by letting end-users experience these remapping prototypes, the second part evaluated the quality of remapping prototypes authored by RemapVR. The outcomes of the evaluation highlighted designers can benefit from RemapVR's multi-branch authoring procedure to identify and address potential design challenges, create remapping prototypes that ensure user experience, and take inspiration from templates to create novel remappings.

This paper contributed the first immersive authoring tool that facilitated the rapid prototyping of remapped interactions, with a focus on addressing the challenges above via i) summarizing gain configures from various remapping techniques that help designers understand remappings in a more structured way and making it technically feasible for building RemapVR; ii) identifying experiential factors and providing visualized indicators for characteristics of gains as well as sensory conflict, that are important to help designers reasonably apply the remappings; iii) composing the prototyping procedures and methods to help designers iterate and validate the design effectively.

2 RELATED WORK

RemapVR shares similar goals with recently emerging immersive authoring tools for enabling rapid prototyping of VR/AR applications, but is quite varied in terms of the design challenge as it involves integration and authoring support of remapped interactions, and considerations of sensory conflicts.

2.1 Remapping Interaction in VR

VR remappings break the original one-to-one mapping between the virtual and real world to expand interactive spaces, enhance user capabilities, and strengthen perception [3, 26]. Based on spatial attributes, they are classified into repositioning, redirection, and resizing.

To extend interactive spaces in limited physical settings, walk repositioning magnifies user translations [8, 57, 67], while locomotion-facility repositioning uses conveyor belts or elevators to expand walkable areas [59]. Techniques like distractor-induced redirection [45] guide users using distractors (e.g., butterflies) to enable infinite walking. Subtle offsets in curvature-based [54] and bending-based redirection [28] also achieve this, while upright redirection [34, 36] and swimming redirection [7] break posture limits for broader interaction.

To enhance task performance, jump redirection [24] amplifies jump distances and reduces fall risks, while head-turning redirection [41] increases head-turning angles to lower exertion. Body resizing [1] and arm-length resizing [26] expand interaction ranges. Haptic repositioning methods [5] align real objects with virtual interactions, while weight illusion [51] and slow-action repositioning [52] alter time and weight perception.

For non-avatar objects, change blindness repositioning [44] aligns unseen virtual objects with real ones, and object resizing [6] maps real objects to multiple virtual counterparts with various sizes.

The rich remapping technologies and their broad application scenarios gave us the motivation to develop RemapVR. These numerous and various remapping methods provide an important reference for extracting their common configurations to complete the unified description framework, templates, and design space.

2.2 Authoring Tool for VR/AR Interaction

Traditional VR/AR authoring tools, like Unity, Unreal, and their plugins or SDKs [16, 38, 60], typically rely on desktop software with GUI interaction via mouse and keyboard. These tools support features like haptic repositioning [70] and walking redirection [4, 32, 33]. Recently, immersive authoring tools allow designers to create and experience VR prototypes directly within a VR environment [9, 55], offering intuitive, WYSIWYG workflows that reduce iteration cycles and lower barriers for non-experts [65, 72]. Compared to traditional toolkits, immersive authoring tools lack the convenient top-down overview and management capabilities of scenes. However, immersive authoring is still suitable for constructing remappings and addressing sensory conflict challenges. On one hand, seamless switching between creation and experience can significantly accelerate the iteration process. On the other hand, immersive authoring can promptly and effectively convey to designers the effect of remapping on perception and cognition.

Immersive authoring is widely used across VR/AR domains. Tools like VRception simulate the reality-virtuality continuum by rendering environments with varying transparency [19]. In general, most immersive authoring tool follow an input-output event-driven workflow, this entails showcasing and recording the triggering processes as input and the corresponding feedback processes as output, with subsequent connections to bind their relations [65, 69, 72].

Inspired by these studies, we developed RemapVR, the first immersive tool dedicated to remapping. While it shares the input-output event-driven workflow of other immersive tools, RemapVR faces unique challenges, including adhering to mapping rules and addressing sensory conflicts, requiring careful consideration of experience factors.

2.3 Sensory Integration, Conflicts, and Perception Threshold

The human experience of the body and the world relies on multisensory integration within an egocentric, unified frame [46]. Vision provides optic flow through color, disparity, and occlusion [25]; the vestibular sense detects gravity and head motion [23, 68]; and proprioception senses skin, muscle, and joint changes [68]. Conflicts between vision and vestibular inputs often cause motion sickness and impair spatial perception [2, 37], and between vision and proprioception inputs often reduce body ownership and perceptive and controlled accuracy of action [15, 29].

Remappings interfere with sensory integration, affecting spatial perception [12], immersion [53], body ownership [63], illusions [47], and motion sickness [50]. These effects depend on gain types and values [31]. Researchers mitigate sensory conflict by keeping gains within perception thresholds: unperceivable thresholds (subtle gains unnoticed [28]), limited immersion thresholds (gains do not disrupt immersion [56]), and acceptable thresholds (gains are tolerable [53]).

The significant impact of sensory conflicts in remapping has led us to prioritize them as a key experiential factor. RemapVR leverages knowledge of sensory integration, conflicts, and thresholds to help designers evaluate and reduce sensory conflicts.

3 Design Consideration and Pilot Study

The key challenge in remapping applications lies in understanding remapping methods and gains—what they do and how to set them effectively to achieve design goals. Trial-and-error approaches on VR platforms are time-intensive, and current immersive authoring tools do not address these challenges. However, existing examples provide opportunities for designers to learn and innovate. To address this, RemapVR consolidates common remapping configurations from the literature, including gain properties, input-output events, and calculation methods, into a unified representation. This structured approach aids designers in understanding remappings and enables the development of RemapVR.

3.1 Gain Configuration

The core of constructing remapping methods is to calculate the gain between the virtual and real objects [31]. To adopt existing remapping methods and support creating new ones in RemapVR, we characterize gain strategies, perception thresholds, and trigger interactions of 24 remappings collected from Google Scholar, as shown in Table 1. The rule for screening remappings was that the remappings requiring a large number of props, huge space, and difficult-to-understand were filtered out. In the table, *pos* stands for position, *rot* stands for rotation, *dir* stands for moving direction, *sca* stands for scale, *C-L* stands for continuous-linear, *C-NL* stands for continuous-nonlinear, *D* stands for discrete, *dis* stands for distance, *ang* stands for angle, *nsc* stands for no spatial changes, *r* stands for radius, *d* stands for the distance between paired virtual and real objects, *pla* stands for placement relationship event, *col* stands for collision event, and *distr* stands for distractor event.

3.1.1 The gain objects, properties, and axes. RemapVR applies gain to 4 types of targets: the whole body, head, hands, and non-self objects. These objects are frequently tracked with 6-DoF in VR, making them well-suited for remappings. These gains encompass position, rotation, scale, and moving direction attributes, and translate/rotate/scale along/around one or more of the x, y, and z axes.

Most remapping techniques involve a single gain, but more complex ones may include multiple gains. For example, haptic repositioning involves both the translation ratio between the virtual and real hand's movement distance (translation gain) and the angular offset between their movement directions (moving direction gain).

3.1.2 The gain types and calculation methods. Remapping gains in RemapVR fall into 3 types: discrete, continuous-linear, and continuous-nonlinear. Discrete gains occur only once during remapping triggering, disrupting the initial alignment of virtual and real objects. In contrast, continuous gains apply to virtual object properties that respond to ongoing changes in the physical world. Based on whether

Table 1: Summary and analysis of 24 existing remappings

Remapping name	Gain property	Gain axis	Gain type	Gain method	Gain-input	Gain-output	Trigger-input →action-output	Unperceivable threshold	Acceptable threshold
walk forward repos[57, 67]	pos	z	C-L	×	dis	dis	→gain	0.86;1.26	0.69;1.5
walk sideways repos[8]	pos	x	C-L	×	dis	dis	→gain	0.88;1.18	0.61;1.58
locomotion-facility repos[59]	pos	z	D	+	nsc	dis	col→gain	/	2.05m
long jump repos[22, 24]	pos	z	C-L	×	dis	dis	→gain	0.68;1.44	0.51;1.87
high jump repos[22]	pos	y	C-L	×	dis	dis	→gain	0.09;2.16	0.05;2.52
distractor-induced redir [45]	rot	y	C-L	×	ang	ang	pla→distr,gain	0.55;1.47	0.43;1.88
curvature-based redir[54]	rot	y	C-L	+	dis&ang	dis	pla→gain	r_r>22m	r_r>4.5m
bending-based redir[28]	rot	y	C-L	+	dis&ang	dis&ang	pla→gain	r_v/r_r<3.25	r_v/r_r<5.6
static upright redir[36, 64]	rot	x	D	+	nsc	ang	pla→gain	<14°	<35°;>59°
dynamic upright redir[36]	rot	x	C-L	×	ang	ang	pla→gain	1.42	3.2
backstroke redir[7]	rot	x	C-L	×	ang	ang	col→gain	1.35	3.11
breaststroke redir[7]	rot	x	C-L	×	ang	ang	col→gain	1.26	3.02
spin jump redir[22]	rot	y	C-L	×	dis&ang	dis&ang	→gain	0.63;1.44	0.51;1.66
whole body resiz[1]	sca	xyz	D	+	nsc	size	→gain	-0.17;0.32	-0.7;5.74
head-turning redir[41]	rot	y	C-L	×	ang	ang	→gain	0.74;1.24	0.63;1.55
weight-lifting repos [51]	pos	y	C-L	×	dis	dis	col→gain	/	0.58;1.73
self-haptics repos [13]	pos	x	D	+	dis	dis	col→gain	/	d<0.4m
knock-on-wood repos [58]	pos	y	C-L	×	dis	dis	col→gain	0.71;1.17	0.59;1.46
slow motion repos [52]	pos&rot	xyz	C-L	×	dis&ang	dis&ang	→gain	/	0.4;1.78
haptic repos [5, 44]	pos&dir	xz&y	C-L	+	dis&dir	dis&dir	col→gain	d<0.08m	d<0.32m
arm length resiz [26]	sca	z	D	+	nsc	size	→gain	-0.11;0.25	-0.69;2
reach-bounded repos [48, 66]	pos	z	C-NL	×	dis	dis	→gain	/	/
change blindness repos[44]	pos	xyz	D	+	nsc	dis	pla→gain	d<0.1m	d<0.27m
non-self resiz[6]	sca	x	D	+	nsc	size	→gain	-0.11;0.46	-0.43;0.95

the gain parameter is constant, continuous gains are further divided into linear (with fixed parameters) and nonlinear (with dynamically changing parameters).

According to existing literature, continuous gain is typically applied by adding or multiplying a value to a target property along a specific axis in each frame. Thus, the calculation methods for continuous gain are categorized as "+" and "×". For discrete gain, a more intuitive approach is to "add an offset value" once during VR initialization rather than "multiply," so all discrete gains use the "+" method exclusively.

3.2 Input-Output Settings

Many immersive authoring tools for interactive content utilize an input-output event-driven workflow [65, 69, 72]. This involves demonstrating and recording a gesture or action in the real world (input event) and the corresponding feedback effect in VR (output event), then linking the two to define an interaction process. RemapVR also follows this workflow to build remappings, requiring the extraction of input and output events to construct gains, as well as input and output events to define the remapping interactions (i.e., how the gain is triggered).

To build remapping gains, RemapVR uses changes in distance, angle, or size from the spatial trajectories of the physical body, head, hands, or non-self objects as gain inputs (as shown in Column 6 of Table 1). The corresponding spatial changes in VR are used as gain outputs (as shown in Column 7 of Table 1). Among them, the gain input is no spatial change for discrete gains because only the virtual target undergoes a one-time spatial change.

To construct remapping interactions, we summarize the trigger-input events and action-output events in Column 8 of Table 1, with the two separated by an arrow (→). In many cases, gains are automatically activated at application startup, no additional triggering conditions are required. Moreover, gains are often triggered by collision events or specific spatial relationships between objects. Specially, some remappings require generating a distractor (e.g., butterfly, hummingbird, or pedestrian) to visually guide the user along a designated path when the gain is triggered [45].

3.3 Perceptual Thresholds

Unlike other content authoring, remapping must address both functional requirements and the mitigation of sensory conflicts. Generally, larger gain parameters generally amplify sensory conflicts, leading to negative user experiences such as motion sickness, reduced spatial perception accuracy, and diminished immersion or body ownership [31, 57]. Perceptual thresholds are established based on remappings' parameter sizes to ensure that the sensory conflicts they induce remain within limits, minimizing their negative impact on user experience. RemapVR uses this to grade the parameter sizes and provides critical references for the design of sensory conflict visualization in subsequent systems.

As discussed in Section 2.3, when gain parameters are kept within unperceivable thresholds, the impact on user experience is minimal. However, gain values within unperceivable thresholds are usually small, limiting the scenarios where the corresponding remapping techniques can be effectively applied. For instance, it is challenging to apply unperceivable curvature-based walking redirection in a limited physical space. Therefore, we also consider another perception threshold-the acceptable threshold [53]. When gain parameters fall between the unperceivable and acceptable thresholds, users' VR experiences are not significantly disrupted and remain tolerable. The perception thresholds will be measured in the next section.

It's worth noting that current perceptual thresholds apply only to constant gain parameters. For nonlinear gains, the perceptual threshold should also be nonlinear, so threshold functions are needed but lack existing measurement methods. RemapVR does not provide perceptual thresholds or sensory conflict visualizations for them.

3.4 Pilot Study for Perceptual Threshold Measurement

The unperceivable and acceptable thresholds for remappings that have been measured in literature are reported in Table 1 using black text. For those not previously investigated, we recruited 8 participants (4 male, 4 female, mean age = 24.625, SD=3.78, age range: 20-32) in our laboratory and measured their perception thresholds through psychophysical experiments. Specifically, we replicated the tasks and scenarios in the literature with an early version of RemapVR including basic functions, and followed the standard procedures to measure the perception thresholds [6, 8, 22, 28, 44]: for each remapping, we divided the possible gain range into 10 parts, using their boundaries as experimental gain values (11 values). Then, a random gain was extracted without duplication from these values and applied to the target object. Participants followed visual guidance for actions and judged whether the virtual distance/angle/size was smaller than the physical distance/angle/size (when measuring unperceivable threshold), or whether the mapping was acceptable (when measuring acceptable threshold). This process was repeated 10 times. The response rate for each experimental gain value was calculated based on the proportion of "yes" in the judgment answers. Finally, response rates corresponding to 11 gain values were fitted to a psychometric function, i.e., correspondence between gain values and response rates. Based on the function, gain values corresponding to 50%, 0%, 100%, 75%, and 25% response rates represented subjective equality points (difficult or ambiguous to distinguish), easily judged points, large perception thresholds, and small perception thresholds, respectively.

In the table, the perception thresholds of the new measurement are shown in the blue text; the "/" in unperceivable thresholds represent one of the purposes of this gain is to deliberately make the user aware of it. Moreover, gains with "×" method usually have two threshold values, one less than 1 and one greater than 1. Similarly, the scaling gains also usually have two threshold values, one less than 0 and one greater than 0.

When designers create new remappings, we encourage them to conduct preliminary measurements of their perceptual thresholds and input these data into RemapVR.

3.5 Coverage of the Design Space

In summary, through the decomposition and analysis of 24 existing remappings, RemapVR established a foundational framework for authoring existing and new gains. This identified a broad design space, which includes individual remappings freely combined from different objects (entire avatar, head, hand, or other objects), property (position, rotation, scale, moving direction), types (discrete, continuous-linear, continuous-nonlinear), coordinate axes (x, y, z), methods (×, +), and parameter sizes, as well as combinations of these individual remappings. Additionally, we use perceptual thresholds as soft constraints on parameter sizes to ensure a positive user experience for end users.

4 System Design of RemapVR

Based on Section 3, this section aims to explore functions and interfaces that address the design challenges, as well as authoring procedures for RemapVR to enable designers to effectively design, iterate, and experience remappings.

4.1 User Interface

Designing remapped interactions in VR poses challenges, requiring designers to be mindful of spatial mappings and facilitate intuitive editing in an iterative design process. The user interface features an avatar with a human model representing the end-user. Designers can simulate end-user experiences, controlling the avatar to demonstrate the virtual-real head/hand/body correspondence through body actions, i.e., end-user view (Figure 2a). However, this view may lead to spatial perception confusion and motion sickness due to sensory conflict, and physical fatigue due to embodied action demonstration (e.g., walking, rotating, jumping, etc.). To address this, RemapVR introduces an observer view, designers control another avatar that only renders two handles and manipulate the head/hand/body of the end-user avatar from a third-person perspective (Figure 2b). This allows for a clearer understanding of remapping effects and facilitates comfortable adjustments.

To enable designers to design the physical and virtual scenes required for remapping easily, RemapVR includes two types of objects: virtual objects and physical objects represented by virtual models. From the end-user perspective, designers can freely switch between the virtual scene and the simulated physical scene. In the observer view, designers can see both the virtual and simulated physical scenes simultaneously, with the two distinguished by opaque and semi-transparent rendering [19] (Figure 2b).

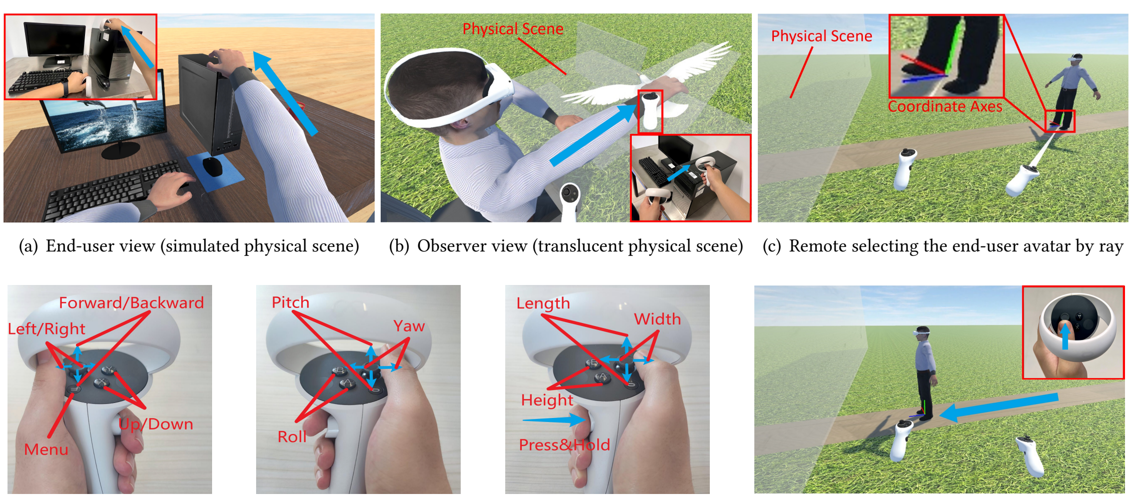
RemapVR enables precise editing of spatial properties (e.g., position, rotation, scale) for various objects (e.g., avatars and non-avatar objects) to build scenes and define remappings. For nearby objects, designers can use VR controllers for direct manipulation by hand actions. For distant objects, designers select them using handle ray, visualizing coordinate axes (Figure 2c), and then use handles' joysticks and buttons for translation (Figure 2d), rotation (Figure 2e), and scaling (Figure 2f). The translation/rotation/scaling directions are based on the target model's coordinate system (Figure 2g).

4.2 Designing Virtual and Simulated Physical Scenes

Similar to other immersive authoring tools, designers initiate a project in RemapVR by creating the application scene and defining the interaction area. The end-user avatar is automatically added. Standard 3D models (e.g., tables, chairs, walls) are available in the model library, and designers can import them or other custom models. Designers can align virtual objects with real ones, enhancing awareness during remapping edits.

4.3 Authoring Remappings in Editing Mode

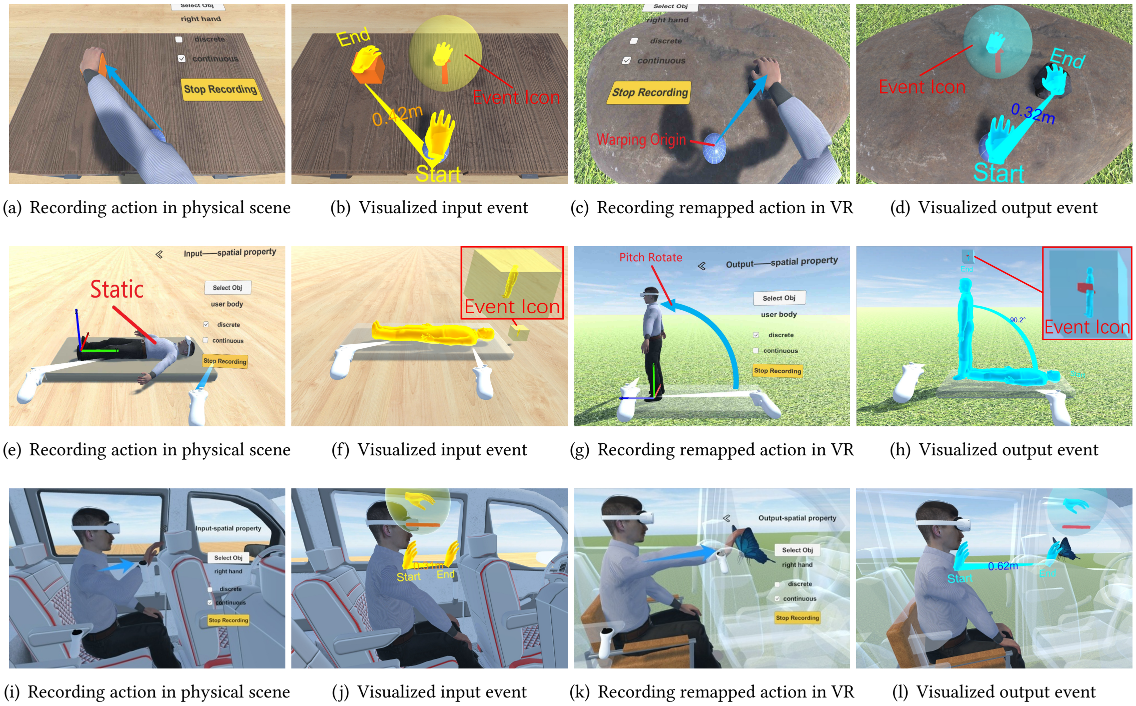
In Editing Mode, designers employ an intuitive input-output event-driven workflow [65, 69, 72]. They demonstrate input and output events through embodied actions (end-user view) or handle control (observer view), and then pair them. This workflow aligns well with RemapVR's purpose, as remappings involve changing the mapping of physical actions to virtual responses. Importantly, Editing Mode provides a lot of visualizations (e.g., input/output trajectories, gain setting, sensory conflict, etc.) to help designers overcome design challenges for building reasonable remappings.



(a) End-user view (simulated physical scene) (b) Observer view (translucent physical scene) (c) Remote selecting the end-user avatar by ray

(d) Controlling position (e) Controlling rotation (f) Controlling scale (g) Remote controlling end-user to move forward

Figure 2: Two view and interaction methods of RemapVR



(a) Recording action in physical scene (b) Visualized input event (c) Recording remapped action in VR (d) Visualized output event

(e) Recording action in physical scene (f) Visualized input event (g) Recording remapped action in VR (h) Visualized output event

(i) Recording action in physical scene (j) Visualized input event (k) Recording remapped action in VR (l) Visualized output event

Figure 3: The process of building gain input and output events (the first, second, and third rows show the recording of haptic repositioning in end-user view, upright redirection and reach-bounded repositioning in observer view, respectively.)

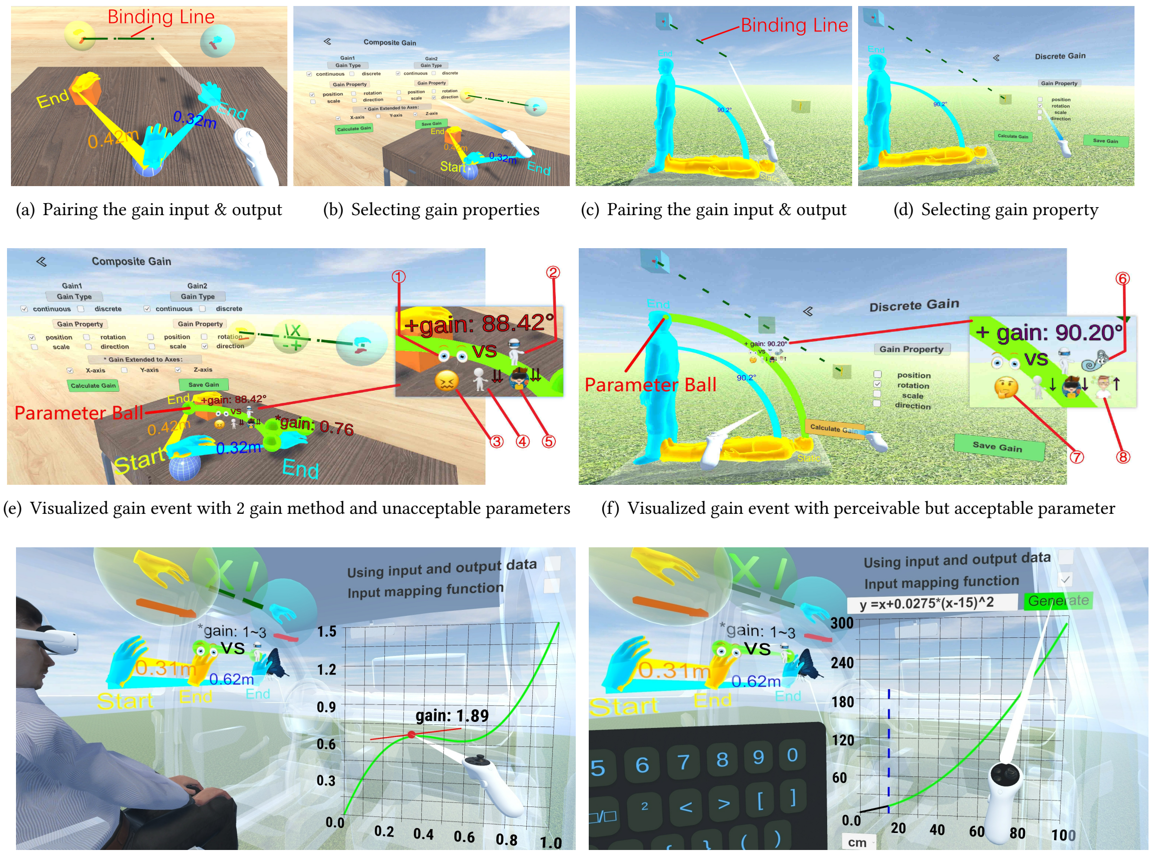
4.3.1 Recording gain input & output event. To build input/output events for the gain target, designers choose the event type (continuous or discrete) from the menu, then select the target objects and press the two handles' trigger buttons simultaneously or click the record button on the menu to begin the recording process. They manipulate the recording object for translation, rotation, and scaling. Continuous events record all the position, rotation, and scale data of the spatial trajectory, while discrete events only record data at the spatial trajectory's start and end moments.

To help designers conveniently review and further adjust remapping effects, ensuring functional requirements are met, RemapVR visualizes target objects, spatial properties, trajectories, and values after recording input/output events. This includes using target-model copies to indicate the gain target, yellow/cyan colors to represent input/output, and sphere/cube icons to distinguish continuous/discrete events. Recorded trajectories are depicted using different line segments, i.e., straight lines for distance changes and arc lines for angle changes, the thick end represents the trajectory beginning and the thin end represents the trajectory end.

In an example of building haptic repositioning with continuous-linear gain [5, 44], designers record the process of the avatar's hand moving from the origin to the target cube in the simulated physical scene as a continuous input event (Figure 3a&b), followed by recording the hand moving towards the corresponding stone in the virtual scene as a continuous output event (Figure 3c&d). For building upright redirection with discrete gain [36], designers record the avatar without spatial changes in the lying position as a discrete input event (Figure 3e&f), and the process of lying avatar rotated to the upright position as a discrete output event (Figure 3g&h). For building reach-bounded repositioning with continuous-nonlinear gain (allowing a user in a confined car interior to touch farther objects in VR) [48, 66], the designer records the end-user avatar's hand moving forward in the narrow physical space until nearly touching the front seat as input (Figure 3i&j), and the corresponding virtual hand fully extending as output (Figure 3k&l).

4.3.2 Constructing gain event via binding gain input and output events. After recording the gain input and output events, designers establish the gain event by connecting icons of gain input and output with binding lines (Figure 4a&c). The binding line, based on continuous/discrete gain type, exhibits a dashed line composed of long/short segments. Designers then specify gain properties (position/rotation/scale/direction) and calculation method ("+" or "×) in the menu (Figure 4b&d), and clicking the 'Calculate Gain' button. Similar to the visualization of input/output events, the green cube/sphere icon and straight/arc line segment represent the gain type and mapping relationship (Figure 4e&f). To cover diverse situations, the system determines gain methods and parameters:

- if the event types of input, output, and gain are discrete, the gain method is set to "+" and the gain parameter is set to the difference between the spatial variation of the output and input trajectories. The rule is built based on all 7 discrete remappings in Table 1.
- if the event types of input, output, and gain are continuous, the event property of gain is position/rotation/scale, and the



(a) Pairing the gain input & output (b) Selecting gain properties (c) Pairing the gain input & output (d) Selecting gain property

(e) Visualized gain event with 2 gain method and unacceptable parameters (f) Visualized gain event with perceivable but acceptable parameter

(g) Setting dynamic parameters by editing virtual-real correspondence curve (h) Setting dynamic parameters by inputting mapping function

Figure 4: The process of building gain events. The first, second, and third rows show the methods of setting gain, visualizing sensory conflict, and expanding the constant gain value to a dynamic one, respectively

input trajectory includes both distance and angle changes (i.e., a curve), the gain method is set to "+", where the gain parameter is the curvature relation between the input and output trajectories. Such a rule is built based on curvature-based redirection and bending-based redirection in Table 1. Otherwise, the gain method is set to "×" and the gain parameter is set to the quotient between the spatial variation of the output and input trajectories. The other 13 continuous remappings in Table 1 comply with this rule.

- if the event types of input, output, and gain are continuous, and the gain property is direction, the gain method is set to "+" and the gain parameter is set to the spatial angle between the moving direction of the output and input trajectories. Such a rule is built based on haptic repositioning in Table 1.

If a remapping contains more than one gain, each gain employs this calculation strategy, determining the gain for each property individually. The gain calculation methods extracted from the remappings in Table 1 simplify the process for designers, shielding them from the complexities of remapping calculations. Notably, these rules not only support RemapVR in creating 24 existing remappings but also provide a unified computational framework for authoring new remappings.

4.3.3 *Referring to visualization of sensory conflict to optimize gain.*

To enhance the rationality and effectiveness of the remappings, adjusting the gain parameters is a crucial step during iteration. We set parameter spheres at two endpoints of the green line segment, which represents the mapping relationship. These parameter spheres allow designers to control the gain parameters by adjusting their positions. During the adjustment process, the visualization of the corresponding input/output trajectories and the mapping relationship dynamically updates in real-time. Once the adjustment is complete, designers can click 'Save Gain' to save the gain event as a profile, which also updates the associated profiles of input and output events accordingly.

In the many experience factors of remapping's iterative process, sensory conflict is critical and unique, often lacking in other authoring contexts. Designers frequently lack the necessary expertise in this area. To address the challenge of ensuring rational iterations, we visualized the types, impacts, and intensities of sensory conflicts induced by remapping prototypes, providing an intuitive reference.

To reduce the cognitive load on designers and make the information easier to understand, we designed corresponding stylized icons for the main senses involved in conflicts and their core impacts, as illustrated in Figure 4e&f. These include icons for vision (① a pair of eyes), proprioception (② a doll wearing a VR headset and performing interactive actions), and the vestibular sense (⑥ a personified vestibular organ). Additionally, we have icons for overall feeling (i.e., unperceivable with a happy expression, ⑦ perceptible but acceptable with a concerned expression, ③ unacceptable with a distressed expression), body ownership (④ a faceless doll to highlight the body feeling), spatial perception (⑤ a person immersed in virtual space), and motion sickness (⑧ a person experiencing dizziness). The symbols ↑/↑↑ represent an increase/significant-increase, while ↓/↓↓ represent a decrease/significant-decrease.

The intensity of sensory conflict is determined by perception thresholds and is visualized using color coding: green, purple, and red represent gain values within the unperceivable threshold, between the unperceivable and acceptable thresholds, and above the acceptable threshold, respectively. For remappings not covered in Table 1, RemapVR offers a threshold measurement function that allows designers to measure and input the perception threshold. The types and impacts of sensory conflicts are determined as follows:

- All remappings entail visual and proprioceptive conflict, as physical body postures and actions are all accurately perceived by proprioception. Visual and vestibular conflicts arise from translations and rotations of the whole body or head, given the vestibular organ's location in the head.
- Perceivable sensory conflicts can affect spatial perception, with the magnitude of visual and vestibular conflicts potentially causing motion sickness, and visual and proprioceptive conflicts impacting body ownership.

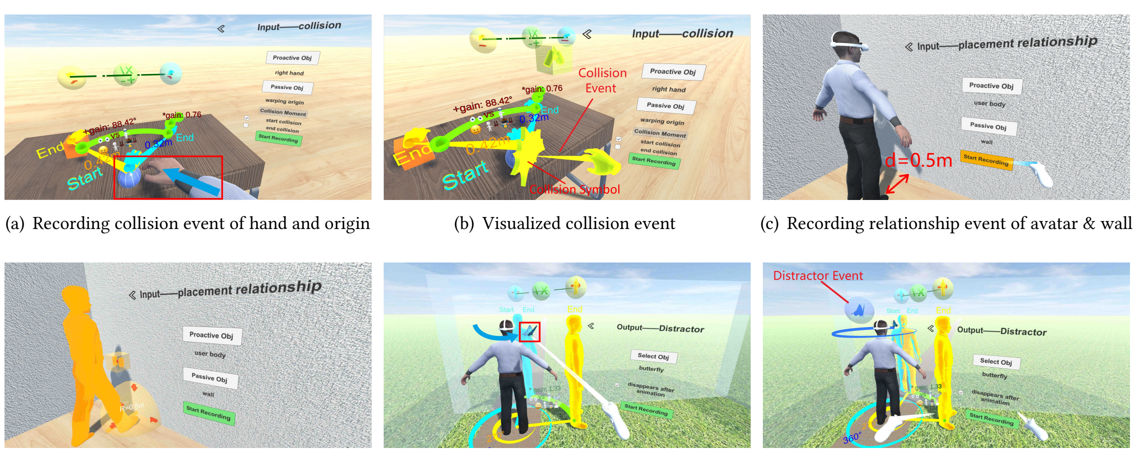
4.3.4 Expanding the constant gain value to dynamic ones. By default, continuous gain parameters are constant, but RemapVR allows designers to create dynamic, nonlinear gains. Designers can double-click the green parameter sphere to open the mapping editor and define dynamic gain parameters via a 2D mapping curve. The horizontal axis represents real-world action distance/angle, and the vertical axis represents virtual actions. Designers can add control points, adjust values/coordinate axis, and edit/reshape the curve (Figure 4g).

Two quick methods help generate the mapping curve: using recorded input-output data or entering a gain function via a virtual keyboard. The first extracts relationships from spatiotemporal data in recorded input-output files, while the second generates curves directly from input formulas. As shown in Figure 4h, designers can directly input the second segment of the go-go interaction [48] function using the virtual keyboard. Designers can add a divider (blue dashed line) to implement the segmented function and separately edit the curves on both sides (or input formulas). The green curve indicates the segment currently being edited.

The range of series gain parameters is visualized, but since perceptual thresholds are hard to quantify (Section 3.3), sensory conflict effects are unpredictable, and related text is shown in black. Despite this, extensive testing in Experiencing Mode is recommended to ensure the gain function's effects are imperceptible or acceptable for users.

4.3.5 Building remapping interaction events. In the final step, it's essential to establish the trigger conditions for gain and any additional actions associated with gain to define the remapping interaction. According to the typical trigger-input and action-output events from Section 3.2, gains are often triggered by collision or specific spatial relationships, typically in conjunction with the induction action of a distractor. Thus, we define collision events, placement relationship events, and distractor events for RemapVR, following the visual programming based on input-output event-driven workflow.

The collision event is defined as an active object touching a passive object. For instance, in haptic redirection [5, 44], users' hands collide with the origin to trigger the gains of moving direction and translation distance. To build such an event, the designer demonstrates the process of using the hand (active object) to collide with the origin (passive object), and determine trigger timing from the



(a) Recording collision event of hand and origin (b) Visualized collision event (c) Recording relationship event of avatar & wall

(d) Visualized placement relationship event (e) Recording butterfly path as distractor event (f) Visualized distractor event

Figure 5: The process of building 3 remapping interaction event

menu (Figure 5a). Event visualization includes model copies of the active and passive objects, a collision symbol, and a cube icon with yellow-green colors (Figure 5b).

The placement relationship event is defined as when an active object and a passive object achieve a spatial relation. For instance, in distractor-induced redirection [45], the end-user avatar triggers the distractor and rotation gain when within 0.5m of a physical wall to avoid walls. To build this, the designer demonstrates the spatial relationship of the end-user avatar (active object) and physical wall (passive object) (Figure 5c). The event visualization includes model copies of the active and passive objects, a spatial range symbol, and a cube icon with orange colors (Figure 5d).

Many remappings are only required in specific situations. Therefore, the two aforementioned events can not only serve to trigger the activation of remapping gain but also act as events to deactivate it. For example, using collision with the shore to deactivate swimming redirection [7], and the avatar of the end-user moving a certain distance away from the virtual desk can deactivate haptic redirection [5].

The distractor event is designed to induce the end-user to perform actions along a predefined trajectory to achieve the desired gain effect. For instance, when the end-user is about to walk into a wall, a butterfly (distractor) prompts the user to rotate 360° in the VR environment to stay on their original walking path, while physically rotating only 180° to avoid the collision. To build such an event, the designer selects a butterfly as the distractor, demonstrates the induced trajectory of the distractor, and chooses whether to hide it after the induction is completed in the menu (Figure 5e). RemapVR included common distractor models in the model library, such as butterflies, hummingbirds, and voice/arrows/text prompts. The event visualization model copies of the distractor, induced trajectory, and a sphere icon with blue colors (Figure 5f).

Finally, designers need to bind these interaction events and gain events by connecting their icons with lines to complete the remapping prototype.

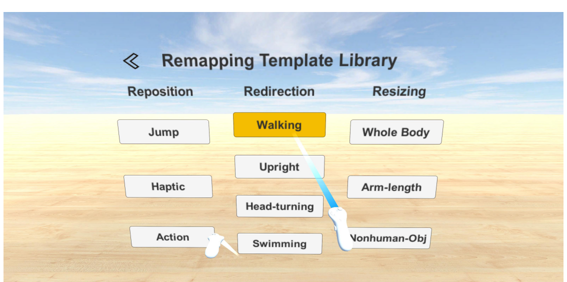
4.4 Libraries and Experiencing Mode

To help novice designers overcome the knowledge challenges of remappings, we recorded all 24 remappings listed in Table 1 into templates using the authoring method of RemapVR and stored them in the template library. Designers can explore interaction events, gain events, and the corresponding input and output events to understand remappings and RemapVR. This also allows them to quickly experiment with these existing remappings to address issues in their target application scenarios. The 24 remapping templates are categorized into 10 functional groups, as shown in Figure 6a. Moreover, RemapVR also allows designers to record and store their novel remappings in a custom library, whether built upon existing templates or created from scratch.

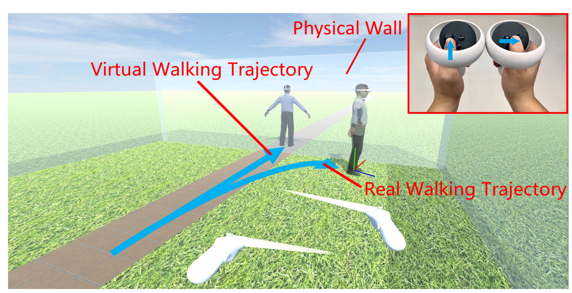
Experiencing mode enables designers to test and experience the effects of remappings. In this mode, RemapVR processes all events and their connections in the scene, loads the remapping profile, monitors trigger events, applies settings to corresponding target objects, and generates distractors (if any). In this mode, designers can manipulate the end-user avatar's action from the observer view while testing and comparing the effects before and after remapping (Figure 6b&d). They can also take on the role of the end-user to experience the remapped interaction from the end-user view (Figure 6c&d). If the designers find the remapping unsatisfactory or inconsistent with their goals, they can switch back to the editing mode to iterate on the design.

4.5 Example Application of Combining Multiple Remappings

RemapVR enables the combination of multiple remapping techniques in a single application to handle complex scenarios. Designers should consider potential conflicts between remappings to avoid gain effect overlap. Here, we show a example application for addressing comprehensive scenarios. Consider a virtual museum with three 40x40 meter floors and many virtual interactive exhibits,

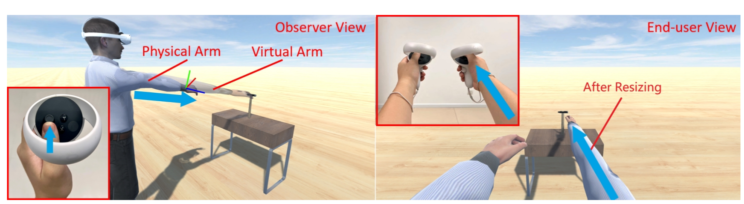


(a) Template library with 10 function classifications



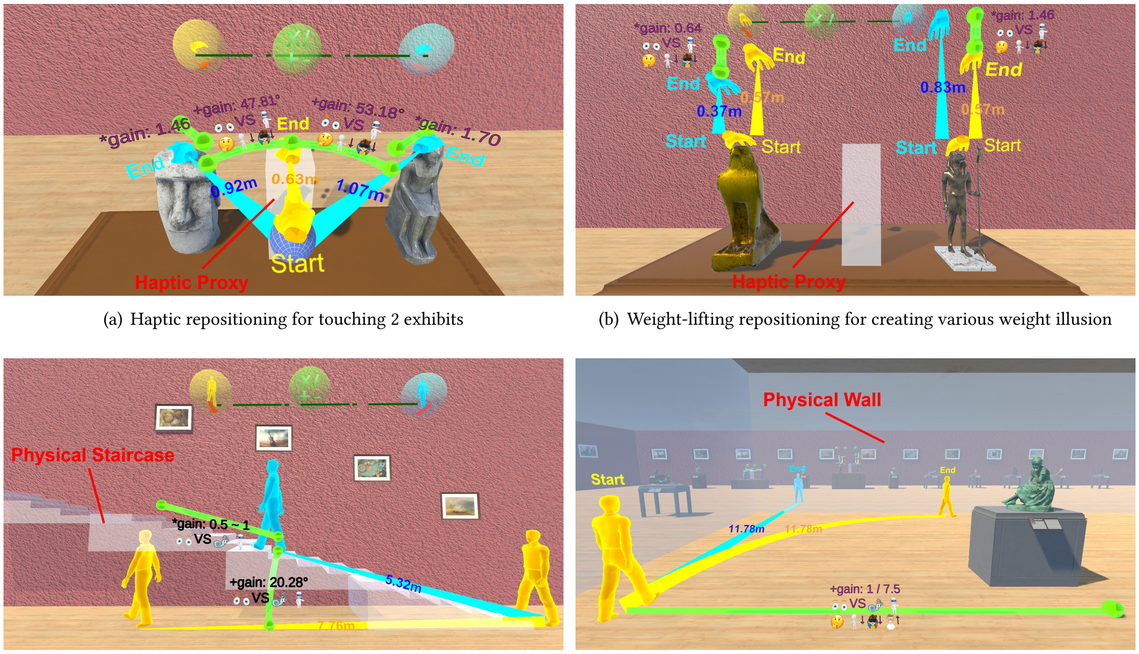
(b) Testing the application effects of walking redirection in observer view

(c) Experiencing walking redirection



(d) Testing/experiencing arm length resizing in observer/end-user view

Figure 6: The template library based on 24 existing remappings and testing/feeling the remapping effects in Experiencing Mode



(a) Haptic repositioning for touching 2 exhibits

(b) Weight-lifting repositioning for creating various weight illusion

(c) Staircase remapping for creating illusion that the climb is getting harder

(d) Curvature-based walking redirection for avoiding physical obstacles

Figure 7: An example application of combining multiple remappings in a virtual museum

while only a 20x20 meter physical floor and low-cost haptic proxies of exhibits are available.

To meet these requirements, designers could use RemapVR to design 5 remappings as follows:

- **Haptic repositioning**[5]: allows one physical cuboid to represent two adjacent vritual exhibits (Figure 7a).
- **Weight-lifting repositioning**[51]: adjusts hand movement speed to create heavier (i.e., reducing the lifting speed) or lighter (i.e., increasing the lifting speed) illusion when the user picks up a virtual exhibit (and its corresponding physical proxy) (Figure 7b).
- **Staircase remapping with non-linear gain (customized)**: creates the illusion of climbing stairs by rotating the user's forward motion upward and using dynamically changing gain parameters to gradually decrease the distance mapping ratio, simulating the increasing effort required in the later stages of climbing (Figure 7c).
- **Curvature-based walking redirection**[54]: induces users around walls in the physical space (Figure 7d).
- **Change blindness repositioning**[44]: adjusts the positions and orientations of all virtual booths and exhibits instantly when participants look at the ceiling or the floor, to address the misalignment between virtual exhibits and physical haptic proxies caused by walking redirection.

4.6 Authoring Procedure for Various Authoring Requirements

To effectively meet designers' authoring needs across different application scenarios and address the design challenges, we propose an authoring procedure. First, designers import or build the virtual and physical target scenes. They then test the built-in remapping templates to check whether they meet the functional requirements. If the templates are sufficient, the process moves on to iteration and experience, as shown in the yellow parts of Figure 8. If not, they need to create new remappings, measure their perception thresholds, and iterate/experience them, as depicted in the blue parts of Figure 8.

During the iteration of gain parameters, designers need to weigh functional satisfiability with various experiential factors (cyan part of Figure 8). Generally, designers aim to find an optimal parameter that ensures all experiential factors are well-addressed. However, some factors may be difficult to optimize simultaneously in certain target scenarios. For example, in the case of long jump redirection, smaller gain parameters reduce sensory conflict but may increase physical exertion and the risk of falling. At this time, designers need to find an almost optimal parameter through trade-offs to ensure the end-user experience is as good as possible.

Specially, when the virtual or physical scene can be adjusted to accommodate the optimal remapping parameters, designers can further modify the scenes based on optimal gain parameters to achieve the best remapping effect, as shown in the green parts of Figure 8.

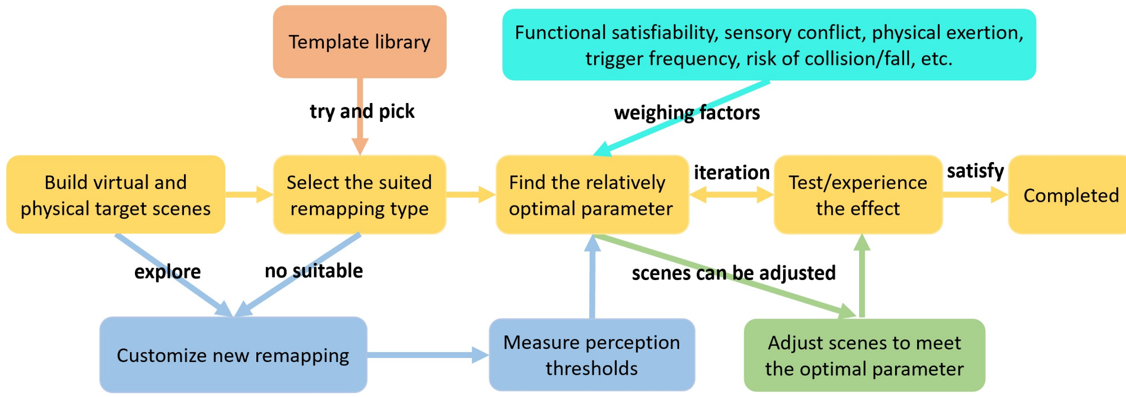


Figure 8: Authoring procedure of RemapVR

4.7 Implementation of RemapVR

RemapVR is built on Unity Engine v.2020.3.36f1c1, and it stores information of all events in JSON-formatted profiles. Currently, RemapVR is compatible with popular commercial VR devices such as Quest2 and HTC Vive. For scenarios demanding detailed hand or object tracking, a marker-based tracking camera is employed.

5 User Study

Following the evaluation strategies of HCI toolkits [30], this study aims to determine whether RemapVR's authoring procedure (Section 4.6) assists designers in effectively coping with various practical scenarios and overcoming knowledge and iterative rationality challenges. The authoring tasks include solving open propositions using existing remappings and freely creating new remappings. The evaluation relies on end-users' feedback on these remappings.

Additionally, we validated the benefits of RemapVR's three core functions-mapping visualization, dual views, and sensory conflict visualization-through an ablation experiment (removing functions to assess their impact). Details and results are provided in the supplementary materials due to space limitations.

5.1 Experimental Tasks

We set the following two experimental tasks.

T1 - Using the templates to complete propositions: We introduced six propositions, outlined in Table 2. Each two of the propositions addresses specific design focuses, corresponding to the yellow and green parts of the authoring procedure in Section 4.6. ① involves selecting a suitable remapping method from multiple available templates based on the target application scenario, ② entails finding almost optimal gain parameters by weighing experiencing factors, and ③ focuses on finding optimal parameters and adjusting virtual/real scenes for meet the parameters.

T2 - Custom new remappings: To evaluate whether designers can get a deeper understanding of remapping and draw inspiration to create innovative custom remappings after using the template library in T1, participants were asked to independently custom a novel remapping prototype. The newly created remappings are typically manifested in two ways: introducing new gain configurations (e.g., different target objects, properties, axes, types, or methods from existing gains) and using existing gains to realize new uses.

5.2 Participants, Procedure, and Evaluation

Under the ethical approval from a local university, two participant groups were engaged: one group tasked with crafting remapping prototypes using RemapVR (design group), and the other group designated to experience and assess these prototypes (evaluation group). The design group comprised 14 participants (7 male and 7 female, mean age=23.5), who underwent orientation to templates and functions, practiced creating various events, and were then instructed to complete a random proposition in T1 and custom a new remapping in T2 (total 28 remapping prototypes). Notably, participants in this study were required to independently and deeply think key experience factors.

In the evaluation group, a new cohort of 7 participants (4 male and 3 female, mean age=22.25) from a local university with non-design majors was recruited. Each participant was assigned the task

Table 2: The propositions of Task 1 in User Study

No.	Proposition content	Focus
1	Enabling end-user to walk a 10m single-plank bridge in a 5m*5m physical room	①
2	Allowing end-user to pick fruit from a tall fruit tree	①
3	Allowing end-user to dunk more easily by high jump repositioning	②
4	Allowing seated end-users to look around more easily by head-turning redirection	②
5	Selecting a location for a physical cube to serve as the haptic proxy for 3 fixed-position virtual stones	③
6	Setting virtual scene size for end-user with walk forward repositioning in a 5m*5m physical area	③

Table 3: Custom scale for remapping prototypes

No.	Evaluation Metrics (score range: 1-5)
Q1	Practicality/Value
Q2	Ability to fulfill the functional requirements
Q3	Without physical and mental burden
Q4	Body ownership is not affected
Q5	Space perception are not destroyed
Q6	No motion sickness
Q7	Interesting
Q8	Willing to use this VR remapping in the future

of scoring 4 remapping prototypes created by the design group, using a 5-point Likert custom scale (Table 3). To ensure consistency in understanding and scoring criteria, participants received detailed explanations of each scale question. Following this, participants were briefed on the design details and motivations for the remapping they were evaluating, based on interviews with the design group. Using the end-user view, participants tested, experienced, and scored the remapping prototypes in Experiencing Mode, followed by interviews. To maintain scoring fairness, participants took breaks after each prototype review until physical strength and motion sickness returned to pre-experimental levels.

Each participant received US$30 in cash as a reward.

5.3 Experimental Results

We reported raw score distributions of each scale question by percentage-stacked bar charts and discussed their experiences through interview results. The proportion of high and low segments in the score distribution reflected the designers' ability to use the authoring tool and its authoring procedure to solve design challenges [65, 69, 71, 72].

5.3.1 Remapping prototypes of propositions. In the design group, participants efficiently completed T1 with an average time of 5.5 minutes. All participants (100%) acknowledged that the template library enhances the authoring efficiency of remapping prototypes. Additionally, the majority of participants (13 people, 93%) expressed confidence in the effectiveness and reasonableness of their authored remappings for propositions. For instance, the No.6 participant stated, "I can quickly identify the factors that need to be weighed and iterate gain rapidly to find the parameters that I think are suitable."

In the evaluation group, the ratings of the design group's remapping prototypes are presented in Figure 9a. The colored bars indicate the number of participants assigning each score. The proportions of high segments (4-5 points) from Q1 to Q8 were 71.4%, 78%, 71.4%, 57.1%, 71.4%, 50%, 42.9%, 71.4% respectively, and the proportions of low segments (1-2 points) were 7.1%, 7.1%, 7.1%, 14.3%, 7.1%, 21.4%, 21.4%, 7.1% respectively. For the average score of all questions, 7 (50%) remappings received scores ≥ 4 points, and all 14 (100%) remapping prototypes scored ≥ 3 points.

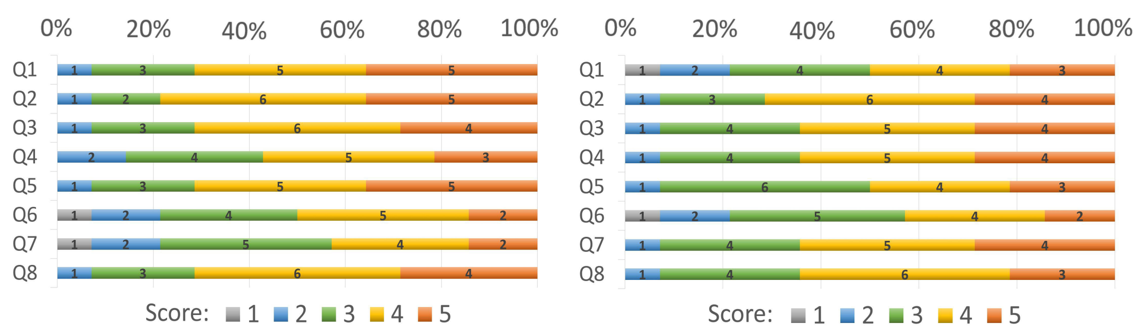
5.3.2 Custom remapping prototypes. In the design group, all participants successfully authored new remappings, with two prototypes found to be similar. The 13 types of novel remappings were shown in Table 4, and the top four highest-scoring remappings (No. 1, 5, 8, 11) were displayed in Figure 10. Participants demonstrated efficient authoring of new remappings, averaging 10.2 minutes. Despite facing greater challenges than propositions, the majority (10 people, 71.4%) expressed confidence in the quality of their created remappings, showing the system's support in turning novel ideas into concrete prototypes that can ensure a good user experience.

In the evaluation group, the score distribution of the 14 custom remapping prototypes was shown in Figure 9b. Among them, the proportions of high segments (4-5 points) from Q1 to Q8 were 50%, 71.4%, 64.3%, 64.3%, 50%, 42.9%, 64.3%, 64.3% respectively, and the proportions of low segments (1-2 points) were 21.4%, 7.1%, 7.1%, 7.1%, 7.1%, 21.4%, 7.1%, 7.1% respectively. For the average score of all questions, 4 (28%) remappings were ≥ 4 points, and 14 (100%) remappings were ≥ 3 points.

6 Discussion

6.1 The Process of Using RemapVR to Solve Authoring Challenges

Overall, the user study indicates that designers can benefit from RemapVR's functions, UI, and authoring procedure, effectively identifying and addressing design challenges to create remapping prototypes that are well-received by end-users.



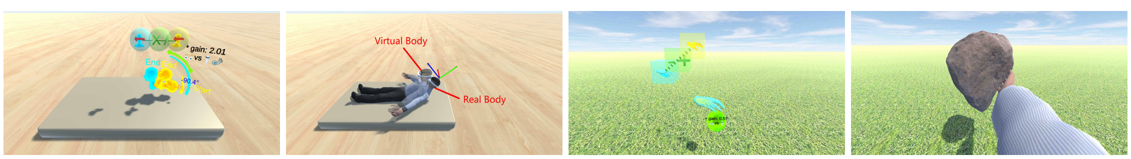
(a) The scores of 14 remapping propositions

(b) The scores of 14 custom remapping prototypes

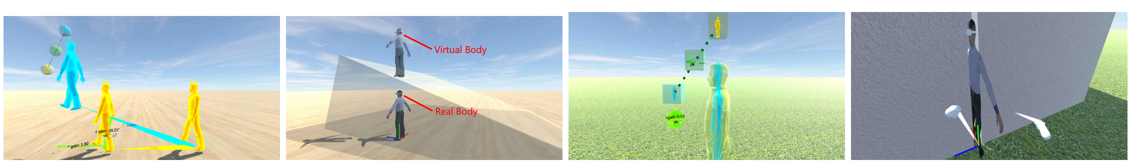
Figure 9: Score distribution of authored remappings, the value represents the remapping number that achieves each score

Table 4: New custom remapping prototype by design group

Custom Remapping	Function
1. Look up/down redirection	Using continuous rotation x-axis "×" gain to the head for solving the problem of difficulty raising and lowering the head while lying down.
2. Fast action	Applying continuous translation xyz-axis "×" gain to hands and head for faster attacking or dodging. Two participants designed this remapping.
3. Walking direction repositioning	Applying the gain of haptic redirection (continuous moving direction y-axis "+" gain) to the avatar to help avoid physical obstacles while walking.
4. Strengthened bend over/squat	Applying continuous translation y-axis "×" gain to head and hands for easier grab virtual objects on the ground or drill through low caves.
5. Big arms	Applying discrete scale xyz-axis "+" gain to the arm for making end-user feel stronger and able to lift larger virtual objects
6. Spider-man redirection	Applying discrete rotation x-axis "+" gain to avatar, redirect end-user in prone position crawling on the ground to climb along a tall building.
7. Curvature haptic redirection	Applying the gain of curvature-based walking redirection (continuous rotation y-axis "+" gain) to the hand for redirecting the hand to the physics object imperceptibly.
8. Uphill/downhill repositioning	Applying continuous moving direction x-axis "+" gain to the avatar for making the physical ground/small-slope appear steeper to the end user walking on it.
9. Vertical haptic repositioning	Applying continuous moving direction x-axis "+" gain to hand for making a physical high or hanging object as the haptic proxy of multiple virtual mid-air objects.
10. Body weight change	Applying discrete size xz-axis "+" gain to avatar for making the body thicker/thinner to increase avatar's strength/agility.
11. Paper man	Applying discrete scale z-axis "+" gain to avatar, making the end-users feel they are thinner so that they can pass through narrow passages.
12. Deft joints	Applying continuous rotation xyz-axis "×" gain to hands for expanding the range of hand rotation (e.g., turning the virtual knobs more).
13. Side jump repositioning	Applying continuous translation x-axis "×" gain to avatar for making dodging easier.



(a) Look up/down redirection (b) Testing in observer view (c) Big arms (d) Experiencing in end-user view



(e) Uphill/downhill repositioning (f) Testing in observer view (g) Paper man (h) Testing in observer view

Figure 10: The top 4 of custom remapping prototypes

Participants efficiently filtered templates and effectively addressed proposition tasks with diverse design focuses. In design focus ①, they initially identified potential templates meeting application scenario requirements (e.g., walk forward/locomotion-facility repositioning, distractor-induced/curvature-based redirection, whole body resizing in No.1 proposition; high jump repositioning, arm length/whole body resizing in No.2 proposition) and then selected the most suitable one through experience and consideration. For design focus ②, participants quickly defined and balanced multiple factors (e.g., falling risk, physical effort, sensory conflict in No.3 proposition; look around range, sensory conflict, and neck comfort in No.4 proposition) to find the gain parameters as close to optimal as possible. In design focus ③, the majority (12 people, 85.7%) quickly found optimal parameters with 1-2 iterations and adjusted the virtual/physical scene for the best remapping effect.

These processes demonstrate how RemapVR and its authoring procedure effectively assist designers in overcoming diverse design challenges across various target application scenarios.

Here, we summarize the typical experience factors that participants weighed while authoring remappings to meet functional requirements. For continuous remappings related to walking, designers needed to consider physical exertion, the risk of colliding with obstacles, and the walkable distance after remapping. For continuous remappings related to jumping, considerations included jumpable distance, physical exertion, and the risk of falling. For head-related continuous remappings, designers evaluated the range of head action and neck comfort. For hand-related continuous remappings, they considered the range of hand action, physical exertion, and joint comfort. In the case of discrete remappings, the focus was on ensuring that trigger events and the sudden body/action changes felt suitable and natural.

6.2 The Ability to Create New Remappings Using RemapVR

Overall, we are pleased to find that designers can effectively leverage RemapVR to unleash their creativity for creating new remappings while still identifying and overcoming the associated design challenges as much as possible.

The template library not only enhanced the efficiency of the authoring process but also aided novices in quickly establishing a broad understanding of remapping knowledge and inspired them to create new remappings. Many participants (11, 79%) attributed their design inspiration to template familiarity during the T1. Among the custom prototypes, some applied existing gains to realize new uses/functions (No. 3, 6, and 7), while others introduced new gains (No. 1, 2, 4, 5, and 8-13).

Ultimately, the evaluation group assigned mostly favorable scores (4-5 points) and positive comments to the remapping prototypes. This suggests that designers, following the authoring procedure in Section 4.6, successfully identified and addressed gain-setting challenges, resulting in good remapping prototypes using RemapVR. However, some prototypes received low scores (1-2 points) due to individual body and perception differences between designers and end-users. For instance, a participant's height difference (24cm shorter than the designer) in the No. 3 proposition task affected her dunking ability, leading to low scores in Q2 and Q3. Additionally, a few participants prone to motion sickness gave low scores on aspects like Q5 and Q6 due to vestibular-visual conflict. To overcome these issues in the future, we plan to create diverse end-user avatar models and automatically adjust parameters, such as viewpoint height, when designers play these avatars. To address perception gaps, we aim to broaden the number of subjects measuring perception thresholds, specifically including those prone to dizziness according to the MSSQ [18], enhancing the inclusivity of sensory conflict references.

6.3 Adaptation to Larger Prototyping Workflows

In practical scenarios, remapping is not an isolated feature; rather, it should integrate seamlessly into broader workflows and other authoring tools. Typically, remapping is employed to enhance existing interactive content and experiences. Consequently, remapping authoring is typically done after prototyping the core scenes and interactive content as part of an extensive prototyping process.

Although RemapVR currently operating independently, it has the potential to serve as a plug-in or functional module, seamlessly integrating with both immersive authoring tools and traditional tools (e.g., Unity3D). It shares underlying mechanisms with many immersive authoring tools (such as virtual/physical scene building and input-output event-driven workflows), facilitating the extraction and integration of its unique functions, such as two views, gain calculation framework, and visualization strategies into other immersive authoring tools. Moreover, RemapVR's core functions can be packaged as a Unity3D plug-in/SDK, enabling integration into the conventional Unity3D-oriented prototyping workflow. The existing authoring methods using handles and joysticks can be adapted for mouse and keyboard inputs, ensuring compatibility with other prototyping tools based on traditional UI, if necessary.

Certain VR applications deliberately employ sensory misalignment as a central interaction mechanic. For instance, the vertigo game creates visual-vestibular conflict by obvious remapping for exhilarating roller coaster [14] and swing experiences [61, 62]. The perceptive system generates visual-proprioceptive conflict through remapping to craft magical illusions and novel interaction experiences [27, 49]. In such scenarios, remapping prototyping should take precedence over other content prototyping. Designers can utilize RemapVR initially and then export gain configurations/code to other authoring tools for additional content design.

6.4 Limitations and Future Work

RemapVR currently includes only remappings based on visual manipulation. In the future, RemapVR will consider incorporating remappings based on auditory and haptic manipulation [17, 39, 43] and even complex multisensory remappings. Additionally, future work on RemapVR will explore the integration of a special and promising type of remapping to expand its application scenarios: VR in-place locomotion methods based on body gestures. These include mapping action attributes such as the frequency of alternating taps with the feet [42], the tilt angle of the torso/head [20, 21, 73], or the speed of arm swings [40] to the speed of view translation or rotation. This will encompass more complex mapping functions.

For intricate application scenarios, RemapVR needs expansion to better support concatenating and combining diverse remappings. This includes establishing rules to control conflicting gains from remapping overlays and enhancing the visual elements of the UI. Designers presently have the option to click/drag event icons to hide/move visualizations and address overload or overlap issues. Future enhancements will concentrate on optimizing the UI by integrating intelligent layout functions, adjusting visual elements during event construction for spatial information presentation, and efficiently managing visual load.

In the experience factors that need to be weighed during the iteration process, RemapVR currently only offers visualized references for sensory conflict. Our future plans include introducing visualized references for additional experience indicators (e.g., physical effort, sense of security, action comfort, etc.) to facilitate users in weighing various factors and iterating parameters more efficiently and reasonably.

7 Conclusion

Remapping in VR enhances interaction capabilities in constrained spaces by decoupling spatial mappings between real and virtual environments. However, its adoption is hindered by the complexity of design and the need for programming expertise. To overcome these challenges, we developed RemapVR, an immersive authoring tool that integrates templates for established remapping techniques and extends the design space for creating new ones. Featuring a user-friendly interface, RemapVR empowers designers to leverage existing templates and explore innovative remapping strategies. Our user study demonstrated its effectiveness in addressing scene requirements and overcoming design challenges, highlighting its value for VR industry professionals and researchers investigating remapped interactions.

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