SpatialMouse

A Hybrid Pointing Device for Seamless Interaction Across 2D and 3D Spaces

Sebastian Hubenschmid
University of Konstanz
Germany

Johannes Zagermann
University of Konstanz
Germany

Robin Erb
University of Konstanz
Germany

Tiare Feuchtner
University of Konstanz
Germany

Jens Grubert
Coburg University of Applied Sciences and Arts
Germany

Markus Tatzgern
Salzburg University of Applied Sciences
Austria

Dieter Schmalstieg
University of Stuttgart
Germany
Graz University of Technology
Austria

Harald Reiterer
University of Konstanz
Germany

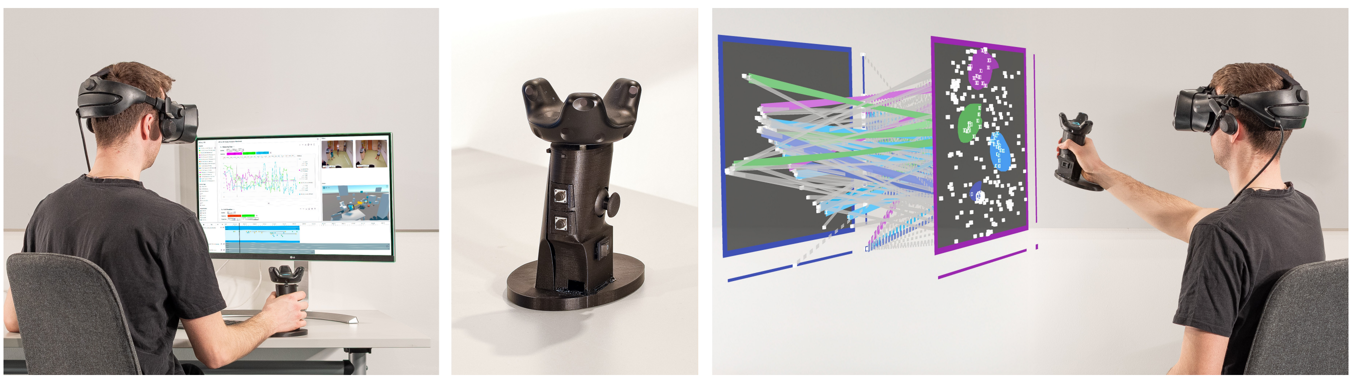

Figure 1: The *SpatialMouse* combines a desktop mouse with a virtual reality controller, enabling seamless interaction across 2D and 3D information spaces in immersive mixed reality environments.

Abstract

We introduce the *SpatialMouse*, a hybrid pointing device that combines the capabilities of a desktop mouse with the spatial input of a virtual reality (VR) controller, enabling seamless transitions between 2D and 3D interaction spaces in immersive mixed reality environments. Holistic usage scenarios in mixed reality involve tasks suited alternately to 2D or 3D information spaces. Yet, existing input devices excel in either 2D or 3D, but not both, making it necessary to switch between multiple input devices (e.g., mouse and VR controller). Our *SpatialMouse* addresses this issue, offering the affordances of a desktop mouse for indirect 2D pointing and the spatial capabilities of VR controllers with six degrees of freedom. In a user study with 12 participants, our prototype significantly reduced perceived task load and improved user experience compared to switching between separate devices. We extract design recommendations to further support such hybrid input approaches.

CCS Concepts

• **Human-centered computing** → **Pointing devices**; **Mixed / augmented reality**; **Virtual reality**.

Keywords

mixed reality, cross reality, hybrid interaction, transitional interfaces, input device

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VRST '25, Montreal, QC, Canada
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ACM ISBN 979-8-4007-2118-2/2025/11
https://doi.org/10.1145/3756884.3766047

ACM Reference Format:
Sebastian Hubenschmid, Johannes Zagermann, Robin Erb, Tiare Feuchtner, Jens Grubert, Markus Tatzgern, Dieter Schmalstieg, and Harald Reiterer. 2025. SpatialMouse: A Hybrid Pointing Device for Seamless Interaction Across 2D and 3D Spaces. In *31st ACM Symposium on Virtual Reality Software and Technology (VRST '25), November 12–14, 2025, Montreal, QC, Canada.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3756884.3766047

1 Introduction

With augmented reality (AR) and virtual reality (VR) becoming increasingly prevalent, users may soon replace their desktop workspace with mixed reality[1] (MR) in their everyday lives to leverage the improved spatial interaction capabilities. However, many common tasks, such as editing documents or browsing the Web, do not benefit from increased spatial capabilities, as they remain firmly grounded on 2D surfaces. We envision that future work in MR will span 2D surfaces and 3D spaces as transitional workspaces.

Although a current head-worn device (HWD)[2] can now sufficiently simulate physical 2D screens [36, 48], the affordances of physical input devices are more difficult to simulate, because their capabilities and constraints vary widely. As a result, users must either intentionally switch between input devices for different information spaces – incurring significant transitioning costs, even with hand tracking [10, 25] – or work with limited input devices.

This situation is unfortunate, since mouse input still offers high accuracy and familiarity for 2D surfaces despite lacking the capabilities for full spatial interaction. In contrast, VR controllers excel at 3D manipulation in immersive environments, but are inherently tiring [15, 20] and less accurate. Users may face hand jitter [8] or a Heisenberg effect of spatial interaction [12, 97]. Free-hand interaction using hand tracking [10, 25] or touchpads [85] could facilitate device switching. However, physical input devices offer advantages for task completion time, accuracy [37, 61], and ergonomics [61].

To enable seamless interaction between 2D surfaces and 3D spaces, we propose the *SpatialMouse* (see Figure 1), a hybrid pointing device suitable for both indirect 2D pointing as well as for 3D input with six degrees of freedom (6DoF). The *SpatialMouse* combines the capabilities of a desktop mouse with a VR controller as one unified device. When used on a table, the *SpatialMouse* acts as a conventional 2D mouse suitable for on-surface operation. When the device is lifted, it automatically switches to a spatial interaction mode, acting as a VR controller with 6DoFs suitable for 3D spaces.

We implemented an initial physical prototype and evaluated its feasibility in a user study with 12 participants. We studied the performance, perceived task load, usability, and user experiences of participants working on an abstract task with frequent switches between 2D and 3D information spaces using the *SpatialMouse* compared to dedicated input devices (i.e., mouse and VR controller). The results of our user study emphasize the feasibility of the concept, indicating that the *SpatialMouse* performs similarly to current dedicated input devices in terms of performance, while reducing perceived effort, leading to a better user experience. In summary, we contribute:

(1) The *SpatialMouse*, a hybrid pointing device that combines the mouse input in 2D and the unconstrained 3D spatial input with 6DoF.
(2) Key insights and implications from a user study, comparing the *SpatialMouse* with a dedicated mouse and VR controller.

We provide the specifications of our physical prototype and the study prototype as open-source project[3].

[1] As the line between augmented and virtual reality becomes increasingly blurry, the term *"mixed reality"* in this work is taken to encompass both [86].
[2] We refer to a *"head-worn device"* instead of a *"head-mounted display"* to emphasize the increase in wearability and capabilities of contemporary hardware.
[3] See https://github.com/hcigroupkonstanz/SpatialMouse

2 Related Work

We look at relevant *transitional workspaces* to demonstrate the need for a unified input device, review *dedicated input devices* for 2D and 3D environments, and explore *shared input across 2D and 3D spaces.*

2.1 Transitional Workspaces

Since physical 2D monitors (e.g., desktops, laptops, smartphones) are still the predominant environment for productivity work, the research area of cross-reality [2, 32] is partially concerned with the integration of 2D surfaces within immersive 3D environments. Prior work in this area finds that *"most cross-reality workflows involve short, temporary movements between VR and desktop"* [96] and that users *"were more willing to transit between [desktop] and VR when the transition cost was lower"* [89]. Several systems have therefore explored the tight integration between 2D monitors and MR environments, such as analyzing data from motion capture [16, 44] and volumetric medical scans [11] or 3D modeling [80]. All these areas represent potential use cases for the *SpatialMouse.*

Although prior work often considers the combination of physical monitors with immersive environments, a contemporary HWD can simply show *"virtual monitors [that] can be used now for real-world work"* [74], thereby enabling purely digital workspaces. Such 2D surfaces can offer distinct advantages beyond the restrictions of physical monitors [35, 74], such as arbitrary sizes or placement within the user's environment. ZIGEN [53] demonstrates how holistic window management for VR environments could integrate transitions between 2D windows and 3D models. Zwin[4] demonstrates how an operating system for VR could involve 2D and 3D windows, requiring both precise 2D interaction but also 3D manipulations.

2.2 Dedicated Input Devices

While we acknowledge the abundance of devices and modalities for 2D input (e.g., touch, stylus, gaze), we focus on the computer mouse, with its long history in HCI[5] as the most established input device for desktop environments. Although alternatives are commonplace for certain devices (e.g., touchpads for laptops, direct touch for smartphones), prior research has shown that they can be significantly slower [85] and less accurate [82] than mouse input.

The consumer market is saturated with custom mice, addressing not only minutiae such as weight and latency [92, 98] but also offering diverse form factors with different trade-offs: While horizontal mice offer more performance, vertical mice promote ergonomic wrist posture [60, 77]. Although some designs reduce performance [50, 77], research proposed slanted mouse designs that optimize ergonomics without compromising performance [60]. Since the *SpatialMouse* should be easily grippable when acting as a VR controller, we base our initial prototype design on such slanted mice, which are similar to off-the-shelf VR controllers.

Similar to the mouse for 2D input, physical 6DoF controllers have established themselves as the leading input device for MR environments [43], despite the wide variety of available 3D input devices [38, 83]. While free-hand input via hand tracking or gaze [75]

[4] www.zwin.dev, last accessed 2025-07-11.
[5] See Bill Buxton's unpublished manuscript *"Human Input to Computer Systems: Theories, Techniques and Technology"* (www.billbuxton.com/inputManuscript.html) and Horst Oberquelle's *"Computer Museum"* (www.fundus.uni-hamburg.de/en/search/expert?collection=computer&q=mouse), both last accessed 2025-07-11.

is becoming more prevalent, studies show that physical controllers can outperform free-hand input [61], partly due to their tactile feedback [8] and technical limitations of hand-tracking [18, 37].

Given the advantages of dedicated input devices, prior research has investigated explicitly switching between devices. All studies conclude that such a switch incurs a significant overhead [10, 25, 76]: For example, a recent study by Cools et al. [25] shows that switching between free-hand interaction and mouse input incurs significant penalties for tasks that require constant switching between 2D and 3D spaces. This overhead is likely greater for physical controllers, as users may avoid picking up another device after working with a mouse [93]. Thus, prior work proposes a *"universal mouse-pointer to handle both 3D and 2D interaction [to reduce] functional discontinuity in the transition between [3D manipulation] and WIMP"* [19].

2.3 Shared Input Across 2D and 3D Spaces

Adapting traditional 2D input devices for interaction within immersive 3D spaces is an ongoing research topic [65]. Prior research has explored translating 2D input into 3D space, for example, by inferring cursor depth from scene context [104], positioning the cursor from multiple views [3] or virtual planes [24], or using multi-touch gestures [5, 23]. These approaches work well with spatial AR [83], which projects the cursor on physical surfaces rather than allowing it to hover in free space [52, 81]. However, given the 2DoF of mouse input, such approaches fall short of 6DoF devices for manipulation tasks [57, 102]. It has been argued that the "*lengthy and dominant reign of the 2D mouse is at an end when it comes to 3D systems*" [49].

The opposite may be true for input devices with 6DoF: They show potential for 3D manipulation tasks [102], but perform worse than dedicated 2D input devices (mouse, touch) to interact with 2D information spaces [14, 25, 47]. Several causes have been identified: The Heisenberg effect of spatial interaction [12, 97] acknowledges that discrete input distorts the spatial position of the input device. Other ergonomic factors include the gorilla arm effect [40, 72] and difficulties due to touching the void [15, 20]. These factors can be partially alleviated by providing users with a desk to stabilize their arms [22, 26]. Note that this approach implicitly provides the user with the option to switch to a dedicated mouse.

Research has therefore explored other input devices suited to both 2D and 3D spaces. Pen input devices, such as the Eye of Ra [11] or SpatialTouch [103], can offer a natural mapping for direct 2D and 3D input. While some researchers suggest that pen input can be a good choice for certain scenarios (e.g., medical use cases [64, 78]), others show that pen input performs worse than 6DoF controllers in task performance and user experience for general 3D sketching and docking tasks [66]. Hybrid user interfaces [28] that combine traditional 2D devices with MR environments could offer a suitable alternative. For example, previous work has employed spatially-aware tablets to interact within MR environments [45, 87], such as 3D slicing [56, 69] or investigated the use of smartphones for 3D manipulations [17, 73]. While hybrid user interfaces can be sufficient to interact with both environments, their ergonomics and efficiency are limited due to the devices' physical constraints.

Thus, we still see the mouse and traditional 6DoF controllers as the optimal choice in their respective environments. To bridge the gap between these two devices, previous research has adapted mice to support more than 2DoF: Examples include the roller mouse [90], Rockin'Mouse [4], VideoMouse [42], two-ball mouse [63], GlobeMouse [31], or the commercially available SpaceMouse[6]. However, these examples employ isometric approaches (i.e., with resistance), which are slower for interaction in 3D space than isotonic inputs (i.e., without resistance) [95]. In contrast, "flying mice" [101] such as the bat [94] or the Cubic Mouse [33] support isotonic input with 6DoF but seem more comparable to contemporary MR controllers, as they lack support for mouse operation. The devices closest to our *SpatialMouse* are Logitech's "MX Air"[7], Sodial's "Air Mouse"[5], and Simgraphics' "Flying Mouse"[5], which supports both mouse operation and isotonic input with 6DoF. To the best of our knowledge, there are no studies that evaluate the efficacy or ergonomics of this device compared to a combination of mouse and MR controller or investigate their potential within transitional workspaces. Our *SpatialMouse* further differs by its design for spatial interaction in MR environments, taking the form of an MR controller and slanted mouse for improved ergonomics. In contrast, devices such as the "Flying Mouse" retain the shape of a traditional horizontal mouse, which could restrict its suitability as an MR controller.

3 Use Cases

Our work is motivated by two main scenarios from prior work that span 2D surfaces and 3D spaces, requiring users to switch between these environments. Apart from our presented following use cases, we envision the *SpatialMouse* as a viable input alternative for various scenarios that span across 2D surfaces and 3D spaces.

3.1 Immersive Analytics

Immersive analytics [21] investigates how technologies such as VR can support analytical reasoning and sense-making. This use case draws inspiration from cross-reality workspaces such as HybridAxes [84] and ReLive [44]. Given the distinct strengths and limitations of 2D and 3D visualizations [88], their complementary use [99] can enable more effective and flexible workflows: 2D visualizations are well-established and effective for providing an overview of dense information, which requires precise interaction. In contrast, 3D visualizations are well suited for inherently spatial data (e.g., motion trajectories) or providing environmental context.

We envision data analysts fluidly [27] transitioning between 2D surfaces and 3D spaces throughout their analytical workflow. For example, to evaluate a user study, an analyst might start with a 2D overview of aggregated data to identify patterns or outliers [44]. In this phase, mouse input is ideal due to its precision and low ergonomic demand, enabling efficient selection and filtering even in dense datasets. To explore spatial data such as motion patterns, the analyst can drag relevant 2D visualizations into the surrounding 3D space [79, 84], where they transform into 3D representations [58, 59]. These visualizations can then be spatially arranged or manipulated using a VR controller, allowing the analyst to examine data from different perspectives or select specific regions within the 3D visualization. By seamlessly switching between 2D and 3D views, analysts can triangulate insights across dimensions, leveraging established techniques such as linking and brushing [51].

[6]https://3dconnexion.com/us/spacemouse/, last accessed 2025-07-11.
[7]ifdesign.com/en/winner-ranking/project/mx-air/36413, last accessed 2025-07-11

3.2 3D Modeling

Cross-reality workspaces for 3D modeling, such as Myr [7] and ZIGEN [53], tightly integrate desktops with immersive VR environments. Spatial interaction using 6DoF controllers supports one-to-one mapping for 3D manipulation that mimics real-world object handling and natural navigation [55]. However, research has highlighted limitations of spatial input for design tasks. Given the ergonomics of extended mid-air interaction [40, 72], designers tend to produce simpler 3D models to reduce strain [67]. In addition, fine motor control can be challenging without arm support [22, 26], and biomechanical constraints may cause translations to be accompanied by unintentional rotations [41]. Research thus proposes *"to split intrinsically 3D operations from operations that are ideally suited to 2D"* [26], for example, by imposing geometric constraints in software [29]. Unsurprisingly, 2D mouse input can provide higher precision for fine-grained adjustments in 3D modeling [6]. As a result, prior work has explored the use of mobile devices to provide greater precision and control in 3D modeling applications [68, 80].

We envision 3D designers switching between 2D and 3D input as their task demands. A typical workflow might begin on a 2D desktop, where a designer uses familiar mouse-based input to navigate files. From the desktop, relevant models can be dragged to the surrounding 3D space, transforming them into interactable objects [53]. Designers can thus perform spatial operations such as extrusion and sculpting, or isolate parts of the 3D model for detailed refinement. However, for fine-grained 3D manipulations, designers may prefer the precision and stability afforded by 2D mouse input [6], taking advantage of its physical constraints. Designers may also constantly switch between editing 2D texture maps and adjusting their placement on the 3D model [55], highlighting the need for seamless transitions between mouse and 6DoF input.

4 SpatialMouse

With the increasing relevance and viability of transitional workspaces, we see the need for an appropriate input device that supports users in the seamless transition between 2D surfaces and 3D spaces. The *SpatialMouse* represents one possible solution (see Figure 2), which allows users to seamlessly switch between indirect 2D pointing input for mouse operations and 3D input with 6DoFs for spatial interactions, without changing the input device[8].

4.1 Interaction Concept

The *SpatialMouse* differentiates between two distinct modes: *mouse mode* and *spatial mode*. The user keeps the same hand posture in both modes, avoiding grip adjustments.

Mouse Mode. The *mouse mode* is activated when the *SpatialMouse* is placed on a surface, allowing the user to operate the *SpatialMouse* like a slanted mouse. Users can indirectly control a cursor on a 2D surface (e.g., desktop monitor) by moving the device like a mouse. In *mouse mode*, input to the cursor is relative and may require clutching: The clutch can be activated by lifting the *SpatialMouse* and moving it back to a neutral position. Although clutching might also activate the *spatial mode* (see below), the *SpatialMouse* seamlessly switches back to *mouse mode* upon being put down again.

[8]Also refer to the supplemental video.

Figure 2: The *SpatialMouse* integrates mouse and VR controller functions, with mode-dependent mappings: *mouse mode* maps buttons to left/right click and the joystick to scrolling; *spatial mode* maps buttons to triggers and the joystick to 2D input. A top-mounted tracker enables 3D tracking, and the baseplate serves as a wrist rest.

Left and right clicks can be triggered by pressing the upper and lower buttons with index and middle fingers, respectively. A joystick mounted near the user's thumb allows for scrolling input, similar to a scroll wheel: moving the joystick up and down moves the content up or down at a speed relative to the joystick's tilt angle, providing precise and adjustable scrolling control. Similarly, moving the joystick back and forth allows for horizontal scrolling, while pressing the joystick simulates clicking on a scroll wheel.

Our initial prototype does not include any additional buttons as often found in many commercial mice (e.g., back, forward). This omission is due to space constraints inside our physical prototype and could easily be addressed by industrial design methods.

Spatial Mode. The *SpatialMouse* activates the *spatial mode* when the device is picked up and no longer detects a surface under its baseplate (approximately 1 cm above the surface). In *spatial mode*, the device provides 6DoF for translating and rotating virtual objects in 3D space. This can be used for direct or indirect 3D manipulations (e.g., via raycasting). Given the lack of standardized control schemes for VR controllers, we designed the *SpatialMouse* to support a basic set of inputs, with a primary and secondary button, as well as a joystick. While the button mapping is application-dependent, the upper button acts as the primary input, similar to the trigger of a contemporary VR controller (e.g., HTC Vive). The lower button acts as a secondary button similar to clicking the touchpad of an HTC Vive controller. In our prototype, the primary button is used to grab objects, the secondary button deletes them, and the joystick supports 2D inputs for precise mid-air control.

4.2 Implementation

In the following, we describe the *form factor*, *hardware components*, and *software* of our *SpatialMouse*. Please refer to the supplemental material for 3D models and assembly instructions.

Form Factor. We followed an iterative design approach for the form factor of the *SpatialMouse* (see Figure 3). Starting with a VR controller attached to a mouse to gain an initial understanding of general ergonomics and input placement, we built clay models and cardboard prototypes to refine the device's shape. Given that the *SpatialMouse* is also intended to be used as a VR controller, we found

(a) Low-Fidelity Mockup (b) Clay Modeling (c) Cardboard Prototype

Figure 3: Our iterative design process involved: (a) attaching a VR controller to a mouse to assess ergonomics and input needs, (b) clay modeling to evaluate form factors for mouse and spatial use, and (c) cardboard prototypes to optimize button placement, hand position, and device size.

horizontal mice to be insufficient for mid-air interaction. Instead, we adopted a design similar to slanted mice and contemporary VR controllers, promoting ergonomic wrist posture in *mouse mode* [60, 77] and ensuring a secure and comfortable grip in *spatial mode*.

Our current prototype has a total height of 17.5 cm and weighs 282 g – including an HTC Vive tracker mounted on top. The case was 3D printed in individual parts, then manually assembled using bolts and glue to allow easy access to its internal components (see Figure 4). A baseplate at the bottom allows users to rest their hands when operating in *mouse mode* and additionally provides structural stability (e.g., enabling the device to stand independently without risk of tipping). A standardized screw on the top supports the mounting of different tracking technologies.

Hardware Components. We use off-the-shelf commodity components with an Arduino Nano ESP32 for input processing and Bluetooth LE 5, ensuring easy replication. We opted for a PMW 3389 optical sensor (as opposed to disassembling a commercial mouse), as it allows for the integration of custom firmware, which is necessary for automatically switching between modes. The mouse sensor, buttons, joystick, and on/off switch are directly wired to the Arduino module. To ensure optimal spatial tracking, we mount a separate tracker (e.g., HTC Vive Tracker) on the top of the *SpatialMouse*, which is otherwise not connected to the internal electronics.

Software. The *SpatialMouse* uses custom Arduino firmware to process and send sensor input to the desktop. We use surface quality readings from the optical sensor to automatically switch between modes: If the surface quality is below a predefined threshold (i.e., mouse is lifted from surface), the internal logic switches to *spatial mode*. This design keeps the *SpatialMouse* self-contained and sends different button events based on the mode over its external interface.

5 User Study

We conducted a user study to evaluate the feasibility of the *SpatialMouse* and consider this user study as an initial step to understand how such a hybrid pointing device can facilitate the transition between 2D surfaces and 3D spaces.

We decided on a within-subjects study design to allow for a direct comparison with dedicated input devices (i.e., a conventional desktop mouse and a VR controller) as a state-of-the-art baseline.

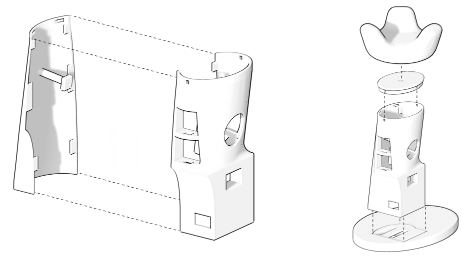

Figure 4: The *SpatialMouse* has a modular 3D-printed case enabling easy assembly and sensor/battery access, and a UNC 1/4′′-20 screw for mounting diverse tracking systems.

5.1 Research Objectives

Our evaluation is guided by three research objectives.

- **RO1 Performance.** How does the *SpatialMouse* affect *performance* when switching between 2D surfaces and 3D spaces?
- **RO2 Task Load.** Does the *SpatialMouse* impact the user's perceived *task load* in tasks that require transitioning between 2D and 3D environments?
- **RO3 Usability and User Experience.** In what way is *usability and user experience* influenced by the *SpatialMouse*?

5.2 Conditions

Our user study includes two conditions: The **baseline** condition uses dedicated input devices (i.e., a mouse and a VR controller) for 2D surfaces and 3D spaces, respectively – involving switches between the distinct modalities. In contrast, the ***SpatialMouse*** condition does not involve switching between distinct modalities, but its usage leads to *mouse mode* or *spatial mode*. To control for learning effects, condition and task order were counterbalanced (i.e., half began with the baseline, half with the *SpatialMouse*). Other hybrid mixed-reality input devices [46] (e.g., Logitech MX Air[7], Eye of Ra [11]) exist, but their input paradigms differ greatly from mouse and VR controllers, so they were not included as conditions.

5.3 Task

We designed an abstract task to replicate workflows that involve frequent transitions between 2D and 3D information spaces as described in Section 3 (see Figure 5) as well as holistic 2D and 3D manipulations. For the proof of our concept, we avoided tasks with high-precision interaction, focusing instead on the device's suitability for both 2D and 3D environments. Participants interact with a simulated *desktop* (i.e., a 2D WIMP interface) and its surrounding 3D VR environment. We chose VR instead of AR to avoid issues with screen legibility and disparities when transitioning cubes from 2D to 3D – following research on VR workspaces [9, 48, 70]. The task combines drag-and-drop, docking, and construction operations: In each step, a colored icon is dragged from the 2D desktop and dropped outside in 3D space to instantiate a 3D cube, which is then placed in a 3D grid. We used a step-by-step workflow that transfers one item at a time from 2D to 3D, enforcing sequential interaction and ensuring frequent transitions. We use the terms *mouse* and *spatial* to refer to the *SpatialMouse*'s input modes, corresponding to traditional mouse input and VR controllers, respectively.

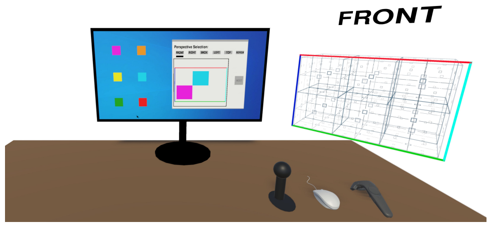

Figure 5: Users switched between a simulated desktop and 3D environment. VR displayed 3D models of the *SpatialMouse*, mouse, or controller based on condition.

(a) SpatialMouse (b) Mouse (c) VR Controller

Figure 6: Study apparatus. The mouse was fitted with a custom 3D-printed attachment for Optitrack targets.

The desktop displays a pool of icons and an interactive plan with six 2D perspectives (top, bottom, front, back, left, right) of the 3D grid. Participants switch between views to determine the correct position of each cube. A color-coded border around the 3D grid aligns with the active perspective to support spatial mapping. Each cube must be placed within a threshold of 1 mm (position) and 5° (rotation). Incorrect cubes can be deleted.

To enforce device/mode transitions, desktop interactions are limited to the mouse (or the *mouse mode* of the *SpatialMouse*), while 3D manipulations are performed using the VR controller (*spatial mode*). Although the *SpatialMouse* enables seamless interaction, we intentionally split the task to align with the baseline's device-switching behavior. Once all cubes of a trial are correctly placed, the grid is highlighted in green, and participants proceed by clicking the "next" button on the desktop. During training trials, visual feedback is provided on individual placements. We designed two task sets with each six different yet comparable trials (i.e., variations of item positions and combinations). The task set order was counterbalanced by alternating the starting set across conditions.

5.4 Measurements

We evaluate *performance* based on task completion time, accuracy of the 3D objects placed, and usage of input modality. Task completion time was measured in milliseconds from the start of the task to the successful completion. Accuracy was calculated as the Euclidean and angular distances between the final and target positions and rotations of each cube. We also analyzed the usage of input modes by measuring the time spent in mouse, switching, or VR modes, based on device movement. For the baseline, switches were counted when one device stopped and the other began moving. We assess *task load* using the raw NASA TLX [39] and *usability* with the SUS questionnaire [13] after each condition. We asked participants about their *user experience* in a final semi-structured interview.

5.5 Apparatus

For all conditions, participants wore a Valve Index HWD (1440 × 1600 px per eye, 120 Hz refresh rate, 108° field of view) connected to a desktop computer (Intel i7 7700K, Nvidia GTX 1080 Ti, 32 GB RAM). Four Valve Base Stations in each corner of the room ensured consistent tracking. For the *baseline* condition, participants switched between a Microsoft Surface Precision Mouse and an HTC Vive Pro controller (see Figure 6). Participants were asked to hold a separate, powered-off VR controller in their left hand to ensure they switched between devices. The VR controller has a similar shape to the *SpatialMouse* and does not contain a wrist strap. The mouse was connected via Bluetooth and fitted with targets for Optitrack cameras. For this, we used a 3D-printed attachment (ca. 15 g) slotted into the front USB port. We manually aligned the virtual mouse model once to match its position in the VR scene. In contrast, the *SpatialMouse* condition used the prototype as described in Section 4. The *SpatialMouse* was tracked with an HTC Vive Tracker, ensuring the same tracking quality as the VR controller. The weight of the *SpatialMouse* was 282 g, the VR controller was 205 g, and the weight of the mouse, including a tracking attachment, was 148 g.

The project was implemented in Unity 2022.3 and is available as an open-source project[3]. Within the VR scene, the desktop monitor simulates a common 16:9 display (~90×48 cm). Each 2D icon on the desktop is 5×5 cm in size and expands to a 30×30 cm cube in the 3D environment, resulting in a size of 90×60×60 cm for the 3D grid.

5.6 Participants

We recruited 12 participants from the local university (1 diverse, 2 female, 9 male) between the age of 21–29 (M = 24.17, SD = 2.37). All participants were undergraduate students from different fields (e.g., computer science, biology). All participants indicated to use their right hand for mouse operation. On a Likert scale from 1 (inexperienced) to 5 (experienced), they rated their mouse proficiency as mostly experienced (M = 4.42, SD = .67). Prior VR experience was mixed (M = 3.33, SD = 1.5), with three participants having no prior VR experience. We recruited participants using flyers advertising the *SpatialMouse*.

5.7 Procedure

Participants signed a consent form, completed a demographic questionnaire, and received an introduction to the study, task, and input methods. They were instructed to complete the task as quickly and accurately as possible. After putting on the VR HWD, they completed two training tasks (with two cubes, then five cubes) for each condition to become familiar with the system and resolve potential issues. This was followed by six main trials (five cubes each; see Section 5.3) per condition. After each condition, participants filled out the raw NASA TLX [39] and SUS [13] questionnaires. Each session ended with a semi-structured interview covering the *SpatialMouse*, missing features, and potential use cases. Sessions took 60–70 minutes, and participants were compensated. The study followed university guidelines for ethics and safety.

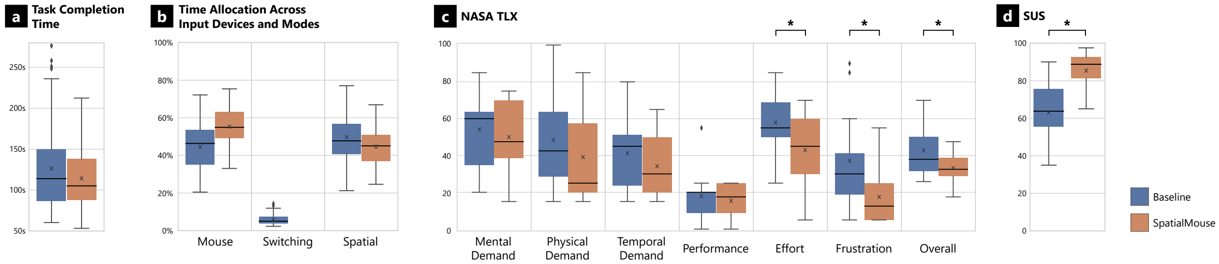

Figure 7: Summary of results. * marks statistically significant differences, lines indicate medians, and crosses represent averages.

5.8 Results

We analyzed the data with a non-parametric approach using a pairwise Wilcoxon test, where appropriate, as a Shapiro-Wilk test indicated that our data did not follow normal distribution. We therefore indicate the medians (*Mdn*) and standard deviations (*SD*) where applicable and assume $\alpha = .05$ for statistical significance. Due to a technical issue, we imputed the final baseline task of Participant 1 with the median of their previous baseline tasks [34]. We transcribed audio recordings from the concluding interview using OpenAI Whisper and verified used quotes manually. Two authors iteratively clustered participants' statements thematically using an affinity diagramming approach.

Performance. Task completion time shows no statistically significant differences (z = -1.448, p = .149) between the baseline (Mdn = 113.71 s; SD = 51.24 s) and *SpatialMouse* (Mdn = 105.11 s, SD = 39.34 s) condition. There were also no statistically significant differences in position accuracy (z = -0.722, p = .47) between baseline (Mdn = 9 mm, SD = 6 mm) and *SpatialMouse* (Mdn = 9 mm, SD = 5 mm). Similarly, we found no statistically significant differences in rotational accuracy (z = 1.124, p = .261) between baseline (Mdn = 2.91°, SD = 1.9°) and *SpatialMouse* (Mdn = 2.9°, SD = 2.03°). In terms of time spent in each mode, participants spent between 2.29–14.31% of each task switching between devices (Mdn = 5.01%, SD = 2.68%) in the baseline condition. Participants spent less time using the mouse during baseline (Mdn = 46.367%, SD = 11.99%) than in its equivalent *mouse mode* during the *SpatialMouse* condition (Mdn = 54.92%, SD = 9.66%). In contrast, participants spent more time using the VR controller during baseline (Mdn = 47.74%, SD = 12.05%) than in *spatial mode* during *SpatialMouse* (Mdn = 45.08%, SD = 9.66%). Since there is no switch in the *SpatialMouse* condition, we refrain from reporting on potentially misleading statistical analyses.

Task Load. The overall score reveals statistically significant differences (z = -2.118, p = .038) between baseline (Mdn = 37.92, SD = 15.95) and *SpatialMouse* (Mdn = 32.5, SD = 9.69). The subscale effort shows a statistically significant difference (z = -2.314, p = .022), with Mdn = 55, SD = 18.64 (baseline) and Mdn = 45, SD = 19.82 (*SpatialMouse*). The subscale frustration shows a statistically significant difference (z = -2.141, p = .036), with Mdn = 30, SD = 27.51 (baseline) and Mdn = 12.5, SD = 15.3 (*SpatialMouse*). We found no statistically significant differences for other subscales.

Usability and User Experience. Analysis of the SUS questionnaire shows a statistically significant difference (z = -2.746, p = .007) between baseline condition (Mdn = 63.75, SD = 16.96) and the *SpatialMouse* (Mdn = 88.75, SD = 9.88). Overall, participants described the *SpatialMouse* as *"intuitive"* (n = 7/12) and *"comfortable"* (n = 6/12). However, participants noted that the baseplate interfered with wrist movement in *spatial mode* (n = 6/12), that the mouse sensor (n = 5/12) and buttons (n = 4/12) felt worse than those of a commercial mouse, and that the *SpatialMouse* felt heavy (n = 4/12). Participants suggested making the *SpatialMouse* more ergonomic by shaping the device to fit one's hand better (n = 2/12) and using a more slanted (n = 1/12) or shape-changing (n = 2/12) design.

All participants appreciated that the *SpatialMouse* reduced the effort of switching, describing the switch as *"instinctual"* (n = 1/12): *"The inhibition threshold was lower to switch to VR"* – P11. In this context, participants positively highlighted that they no longer have to grab different devices (n = 10/12), allowing them to focus more on their task without interruptions (n = 5/12). They were thus more willing to verify the position of the cube on the 2D desktop and click through different perspectives: *"You're more likely to look [at the desktop] again than with the [baseline condition] because you can check it so easily"* – P08. One participant perceived our intentional restriction of having to pick up each cube again after dragging it out of the desktop as a "bug", with four other participants expressing a similar impulse: *"intuitively [. . .] I lifted the [SpatialMouse] while dragging [the cube] out of the monitor"* – P03.

5.9 Discussion

We organize our findings according to our research objectives.

RO1: Performance. We designed the study task to focus on frequent transitions between 2D and 3D interactions to align with workflows described in Section 3. Given that the *SpatialMouse* does not require a device switch, we expected improved task completion times. Despite the tendency of saving about 5% time spent switching between devices (no statistical difference) using the *SpatialMouse*, both conditions did not outperform each other. Results suggest that users spent proportionally more time in the *SpatialMouse*'s *mouse mode* than using the mouse, indicating that the *SpatialMouse* performed slightly worse than a dedicated mouse for 2D input. While this can be partially attributed to its lower-quality mouse sensor or more familiar handling of a conventional mouse, prior findings [50, 77] also show decreased task performance with increasing slant angles. In contrast, spatial interactions were comparable in accuracy to those performed with a dedicated VR controller, suggesting that the *SpatialMouse* is well-suited for 3D input but requires optimization for 2D tasks. The *SpatialMouse* can thus be seen as a compromise that has to fulfill different qualities in one device, while conventional mice and VR controllers are best suited for their environments due to a long history of refinement, including improvements in ergonomics and other design optimizations.

RO2: Task Load. The NASA TLX scores reflected differences regarding effort, frustration, and the overall score. While we observed no differences in mental effort, we anticipate that more complex tasks will benefit substantially from eliminating device switching. However, the NASA TLX questionnaire captures only a retrospective and subjective assessment of task load. To better understand users' mental demands during interaction, we recommend that future work incorporate real-time measures, such as eye tracking [54]. During the concluding interview, participants reported feeling more focused on the task using the *SpatialMouse* rather than being distracted by switching input devices. These findings suggest that the *SpatialMouse* reduces friction, thereby potentially promoting flow.

RO3: Usability and User Experience. The *SpatialMouse* improves usability and user experience using our abstract task. Given the frustration of switching between devices [10, 25, 76], we anticipate similar benefits in real-world scenarios (e.g., immersive analytics). However, leveraging this potential depends on ensuring long-term comfort and usability for mouse operation and spatial usage. Participants suggested improvements to the prototype's ergonomics, which we see as directions for future refinement (see Section 6 below). In addition, such seamless transitions must be equally supported by the interaction design and accompanying interaction techniques: Without this alignment, users may experience friction or frustration, as was occasionally observed under the constraints of our user study setup (e.g., preventing seamless interaction across 2D and 3D spaces to align with the baseline condition).

6 Insights and Implications

Based on our prototype and user study, we discuss design insights for further developments of the *SpatialMouse* and research implications for topics needing further investigation.

6.1 Physical Prototype

Our initial prototype aims to explore the feasibility of our concepts and thus provides several opportunities for improvements.

Input Controls. Building the prototype with commodity components limited the overall performance of the device in terms of sensor accuracy, weight, and button tactility. While this performance gap can be partially addressed through industrial molding and proprietary sensors, such a hybrid input device may also face inherent trade-offs in its design: For example, mouse operation relies on discrete actuators, whereas VR controllers often employ analog triggers. Similarly, our design emulated the mouse wheel with a joystick, but many users may be reluctant to give up the familiar feel of traditional scrolling. While compromises are possible, specialized devices such as mice or VR controllers may still offer the best experience within their respective domains.

Form Factor. The *SpatialMouse* adopts a slanted form factor to provide a good grip that facilitates the transition between *mouse mode* and *spatial mode*. Despite the ergonomic benefits of a slanted design [60], some participants felt unfamiliar with this design, which may have impacted their performance. Likewise, we added a baseplate to support the hand in *mouse mode*, but this limited wrist articulation during *spatial mode*. Although we found the horizontal mouse shape unsuitable for spatial interaction, future iterations could balance the ergonomics of a horizontal mouse with the secure grip required for *spatial mode*. The optimal form factor is likely dependent on individual factors such as hand size and preference.

Grip Change. Prior research [11] and commercial products (e.g., Logitech MX Air[7]) require users to change their grip when transitioning between 2D and 3D operation. While this may offer ergonomic and performance benefits (e.g., in *mouse mode*), our findings suggest that such grip changes introduce friction and thus hinder a seamless transition between interaction modes: *"I actually found the design easy, because you could just put it down in a nice position without having to turn your hand in any strange way"* – P08. By removing the need for users to consciously switch modes – whether through grip adjustments, buttons, or other mechanisms – the *SpatialMouse* enables a seamless transition. Future research should further explore the role of grip changes and weigh their ergonomic benefits against their potential to disrupt fluid interaction.

6.2 Seamless Transition

Despite shortcomings in the initial physical prototype, enabling a seamless transition between 2D surfaces and 3D spaces improved user experience and reduced perceived task load. We discuss how our concept improves upon *switching between devices* and is therefore *promoting fluidity*.

Switching Between Devices. Prior work has primarily investigated switches between 2D surfaces and 3D spaces through combinations of mouse and free-hand interaction [10, 25, 76]. Consistent with this work, we found that switching between a mouse and a VR controller introduces overhead and frustration: *"The most critical [difference] is the fact that I constantly have to let go and pick up another object [during baseline]. And that's really annoying. Because it basically immediately stops me doing the task and makes me focus on picking up the other device"* – P04.

Prior research concludes that *"hand gestures are the prevailing input modality for transitions with 3D objects"* [79]. We argue that this prevalence is in part due to the lack of a suitable unified input device. Our *SpatialMouse* represents a possible device to challenge this status quo: By eliminating a switch between devices entirely, the *SpatialMouse* addresses this limitation and provides seamless interaction between 2D surfaces and 3D spaces. However, further comparative analyses are necessary to unveil potential trade-offs between the *SpatialMouse* and established methods, such as switching between mouse and free-hand input.

Promoting Fluidity. Without a physical switch between devices, the *SpatialMouse* reduces the perceived task load and improves usability. Unsurprisingly, not having to manage device transitions enabled participants to maintain greater focus: *"You don't interrupt your workflow by reaching over. You can concentrate more on the task at hand. I noticed, for example, that I could remember more things during the second trial [with the SpatialMouse]"* – P02. Overall, our findings indicate that the *SpatialMouse* aligns closely with the principles of fluid interaction [27], which emphasizes promoting flow, enabling direct manipulation, and minimizing gulfs of actions.

Notably, by reducing friction – both mental and physical – the *SpatialMouse* encouraged participants to shift between interaction spaces naturally. One participant, for example, attempted to interact with the 2D surface using a VR controller but experienced no such impulses with the *SpatialMouse* – highlighting the need for both hardware- and software-based [96] approaches. Several participants further expressed frustration over intentional study restrictions that prevented fluid cross-dimensional interactions (e.g., cross-dimension drag and drop). Although these constraints were necessary to avoid confounding factors, this also highlights the potential of fluid interaction as supported by the *SpatialMouse*.

6.3 Application Scenarios

With the increasing viability of MR HWDs, we envision future workspaces replacing physical desktop monitors with virtual surfaces [35, 74]. Although our work is framed with immersive analytics and 3D modeling use cases, the *SpatialMouse* is applicable across a wide range of scenarios. For example, game development workflows could benefit from fluid transitions between precise 2D operations (e.g., accurately editing objects in isometric views) and spatial manipulations (e.g., positioning objects within a virtual scene). Such scenarios could reveal additional opportunities and challenges to guide the design of the *SpatialMouse*.

The *SpatialMouse* can also be employed in general MR use cases that do not rely on frequent transitions. For example, MR environments enable the placement of monitors beyond physical restrictions [91]. Yet, mouse usage in such environments can be challenging, as users may need to switch between distant 2D surfaces or navigate large spaces. Here, we see the potential for novel hybrid interaction techniques (see [46]), which could enable the integration of other modalities, such as gaze, to traverse and interact within such spaces and even be useful in non-MR environments.

7 Limitations and Future Work

As our work represents an initial exploration of the *SpatialMouse* concept and was thus evaluated with a small sample size, it has several limitations that provide opportunities for future research.

While our user study demonstrated that our hybrid pointing device outperforms the combination of each device (i.e., mouse and VR controller) in terms of task load, usability, and user experience, we did not investigate how the *SpatialMouse* compares to each device individually. As we cannot claim that our design matches the decades of industry research into mouse ergonomics, the current prototype compromises on mouse operation (e.g., ergonomics) and spatial usage (e.g., weight, maneuverability). However, future studies could employ standardized tasks (e.g., Fitts's law evaluations for 2D [30, 62] and 3D [1]) with larger sample sizes to provide precise benchmarks and identify concrete design improvements for both mouse and spatial usage. Potential directions include shape-changing tangibles [100] that dynamically adapt their form to the current interaction mode or modular attachments. In addition, given the potential ergonomic challenges associated with extended spatial interactions [40, 72], future research should assess the long-term comfort and usability of the *SpatialMouse* in real-world scenarios.

Another limitation is that our study only involved the usage of the primary and secondary buttons, leaving other controls, such as the joystick, unused. Since the specific controls of commercial VR controllers vary between vendors, it may be necessary to tailor the type and layout of these controls based on the expected use case. In addition, our prototype lacks haptic feedback (i.e., vibrations), which is common in VR controllers. Integrating vibration motors to provide haptic feedback increases the weight of the *SpatialMouse*, but could prove useful for both *spatial mode* and *mouse mode* [71].

Lastly, our user study intentionally used an abstract task that emphasized switching between 2D surfaces and 3D spaces. We focused on internal validity instead of fully reflecting holistic, real-world usage contexts. However, ecologically valid usage also includes many confounding factors, such as pointer speed and hand sizes, which provide options for in-depth investigations in future work. In this context, our investigation only involved right-hand interactions. Similarly, we did not consider how off-hand usage factors into device transitions: For example, mouse usage on a desktop is often combined with a keyboard for text input; likewise, 3D manipulations may use bi-manual interaction using two controllers.

8 Conclusion

We introduce the *SpatialMouse*, a hybrid pointing device that combines the capabilities of a desktop mouse with a VR controller, allowing for a seamless transition between 2D surfaces and 3D spaces in immersive mixed reality environments. The *SpatialMouse* is suitable for both indirect 2D pointing of a desktop mouse with 3D input with six degrees of freedom, allowing users to fluidly switch between both by simply lifting or putting down the device. We realized our concept as an initial physical prototype. We evaluated our prototype in a user study with 12 participants using an abstract task involving frequent transitions against dedicated input devices (i.e., mouse and VR controller). Our findings demonstrate that our initial prototype already matches the performance of dedicated input devices in our switching task, while improving perceived task load and usability. We reflect on our findings to contribute design recommendations to guide the design of transitional devices and research implications that provide directions for future improvements. Overall, our work addresses interaction barriers between 2D and 3D spaces, contributing a promising design concept toward achieving fluid transitions in mixed reality environments.

Acknowledgments

We thank Matthias Albrecht, Rasmus Lunding, Shamus Smith, and Cedric Wiese for their constructive discussions and help during early stages of this project. We thank the Alexander von Humboldt Foundation funded by the German Federal Ministry of Education and Research. This research was funded by the *Deutsche Forschungsgemeinschaft* (DFG, German Research Foundation) – Project-ID 251654672 – TRR 161, Project-ID 495135767, by the Fonds zur Förderung der Wissenschaftlichen Forschung (Austrian Science Fund) – Projekt-ID I5912, and by the Villum Investigator grant VL-54492 by Villum Fonden. We acknowledge the use of GPT4 (OpenAI, https://chatgpt.com) at the drafting stage of paper writing and proofreading of the final draft.

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