TactiFlow: Dynamic Rebinding of On-Body Tangible Controls in Mixed Reality

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Abstract

Immersive analytics in mixed reality (MR) often requires users to adjust many virtual parameters, yet only a small number of physical controls can be comfortably worn on the body at once. This creates a key interaction challenge for wearable tangibles: how can a limited set of on-body controls be dynamically rebound to a larger virtual parameter space? We present TactiFlow, a modular forearm-worn tangible interface developed to investigate this rebinding problem. Its slider-and-button modules snap onto a wearable band and can be rebound to different virtual parameters during use. Using TactiFlow, we investigate three embodied linking techniques: Head-Tilt, which uses subtle head motion to target a parameter before module-button confirmation; Gesture-Select, which combines hand-tracked ray selection with tangible confirmation; and Physical-Alignment, which uses computer-vision-assisted spatial alignment between the forearm-mounted module and a virtual control. We evaluated these techniques with 18 participants in an immersive analytics task involving repeated filter adjustment. A preliminary manipulation-validation block verified that the wearable modules provide an effective control substrate relative to in-air manipulation. Our main rebinding comparison revealed clear trade-offs: Head-Tilt enabled the fastest and lowest-effort linking overall, Gesture-Select offered a familiar but moderately slower alternative, and Physical-Alignment, while intuitively grounded in spatial coupling, imposed higher workload and slower relinking under seated use. These findings highlight the importance of rebinding in wearable tangibles for immersive analytics in MR and contribute guidance for future on-body interfaces that must support many virtual parameters using a limited number of reconfigurable controls.

CCS Concepts

• **Human-centered computing → Interaction techniques**; **Mixed / augmented reality**; **Usability testing**.

Keywords

Mixed reality, wearable tangibles, on-body interaction, dynamic rebinding, parameter control, immersive analytics

ACM Reference Format:
Roozbeh Manshaei, Jordan Hoss, Emilia Hyatt, Nour Abu Hantash, Mohsen Ensafjoo, Abril Mure, and Ali Mazalek. 2026. TactiFlow: Dynamic Rebinding of On-Body Tangible Controls in Mixed Reality . In *Proceedings of Graphics Interface 2026*. ACM, New York, NY, USA, 14 pages. https://doi.org/???

1 INTRODUCTION

Immersive analytics systems in mixed reality (MR) increasingly require users to adjust thresholds, tune filters, and manipulate multiple parameters while interpreting complex spatial data [12, 36]. While MR offers rich embodied interaction, it also introduces a practical input challenge: applications may expose many virtual parameters, but only a small number of physical controls can be comfortably worn or accessed at once. For wearable tangible interfaces, this creates a fundamental question of dynamic rebinding: how should a limited set of on-body controls be linked and relinked to a larger parameter space during use?

Tangible interaction offers clear advantages for parameter control. Physical sliders, knobs, and tokens provide tactile cues, proprioceptive stability, and motor structure that can support precise

GI '26, Kitchener-Waterloo, Ontario, Canada

ACM ISBN 978-x-xxxx-xxxx-x/YYYY/MM
https://doi.org/???

and sustained manipulation [7, 31, 35]. Prior work has demonstrated the value of tangibility in MR through handheld widgets, custom controllers, tracked proxies, and arm-mounted interfaces [1, 5, 8, 14, 15, 22, 24, 28, 29, 34, 42]. However, these systems also expose a persistent limitation: unlike virtual controls, wearable physical controls are scarce. A user can only practically wear or hold a few at a time, yet many MR tasks require access to substantially more parameters. As a result, the usability of wearable tangibles depends not only on how well they support manipulation, but also on how easily they can be rebound.

This rebinding step remains underexplored. Existing systems variously emphasize precise tangible manipulation [8, 14, 24, 28, 42, 44], flexible virtual selection through pointing or gaze [19, 20, 30], or on-body haptic support [16, 29], but provide limited guidance on how a small number of worn tangible controls should be rapidly rebound across many virtual parameters. ARm Haptics [16], the closest forearm-mounted precedent, demonstrated the promise of on-body tangible interaction, but its linking workflow required sustained physical-virtual alignment, which users found slow and fatiguing in multi-parameter tasks. More broadly, MR research has not yet sufficiently characterized the design trade-offs among alternative embodied linking strategies for rebindable on-body controls.

We address this problem through TactiFlow, a modular forearm-worn tangible interface developed to investigate rebinding in on-body MR interaction. TactiFlow allows users to manipulate several parameters physically while dynamically rebinding modules to new virtual controls as tasks evolve. Our focus is not simply whether tangible sliders outperform in-air manipulation, but how wearable tangibles can remain practical when a small number of physical modules must serve a larger and changing virtual parameter set.

To study this rebinding problem, we designed and implemented three embodied linking techniques: Head-Tilt, which uses subtle head motion to target a parameter before module-button confirmation; Gesture-Select, which combines hand-tracked ray selection with tangible confirmation; and Physical-Alignment, which uses computer-vision-assisted spatial coupling between a forearm-mounted module and a virtual parameter without requiring continuous alignment during manipulation. Together, these techniques represent different trade-offs among head-mediated targeting, hand-mediated selection, and forearm-mediated spatial coupling.

We evaluated TactiFlow through two tasks with 18 participants using an immersive real-estate analytics scenario. Task 1 served as a manipulation-validation task, comparing wearable tangible manipulation against in-air manipulation with modules pre-linked to parameters. Task 2, the main rebinding task, compared the three linking techniques during repeated rebinding, examining linking speed, relinking performance, errors, workload, and preference. Our findings show that while wearable tangibles provide an effective manipulation substrate, rebinding design plays an important role in the usability of rebindable on-body controls. In particular, Head-Tilt enabled the fastest and lowest-effort rebinding overall, while Gesture-Select and Physical-Alignment revealed different trade-offs in familiarity, spatial intuition, and effort.

This paper makes three contributions:

- TactiFlow, a modular forearm-worn tangible MR interface developed to investigate dynamic rebinding of a small set of wearable slider-and-button modules to a larger set of virtual parameters.
- A set of three embodied rebinding techniques and their empirical comparison (Head-Tilt, Gesture-Select, and computer-vision-assisted Physical-Alignment) showing how these approaches differ in speed, relinking efficiency, error, workload, and user preference in our study context.
- Design implications for rebinding in on-body MR interfaces, including how to balance low-motion targeting, spatial intuition, and control scarcity when supporting many parameters with few wearable modules.

2 RELATED WORK

Interaction techniques for immersive analytics (IA) in virtual and mixed reality include commercial in-air input, handheld controllers, tangible interfaces, and emerging on-body interaction techniques. We review prior work from three perspectives that motivate TactiFlow: tangible controls for parameter manipulation, wearable and on-body tangible interfaces, and mechanisms for linking or rebinding physical controls to virtual parameters.

2.1 Tangible Interaction for MR Manipulation

Tangible controls have long been used to support precise parameter adjustment in spatial and immersive visualization. Physical sliders, knobs, and tokens can provide tactile cues, proprioceptive reference, and motor stability, helping users perform fine-grained adjustments with less overshoot and less reliance on continuous visual monitoring [21, 43, 46]. In immersive analytics, prior work has shown the value of such physical structure. For example, Embodied Axes [9] found that physical sliders outperformed VR controllers for multidimensional axis adjustment, while MADE Axis [37] demonstrated configurable tangible modules for interacting with 2D and 3D scatterplots.

However, most prior tangible systems focus primarily on the manipulation phase itself: once a control is in hand, positioned, or assigned, it can support precise adjustment. Many such systems are handheld or table-anchored [4, 13], which can limit continuity during mobile or extended use and make frequent switching between parameters more cumbersome. Commercial VR/MR controllers improve reach and targeting compared with bare-hand gestures [3, 5, 23, 25], but they still primarily support in-air pointing rather than physically constrained adjustments. As a result, prior work establishes the benefits of tangibility for manipulation, but provides less guidance on how tangible controls should remain practical when users must access more parameters than they can physically hold or wear at once.

TactiFlow builds on this line of work by bringing tangible manipulation onto the forearm and, more importantly, by treating the dynamic rebinding of a limited set of wearable controls as a central interaction challenge rather than a secondary setup step.

2.2 Wearable Tangible Devices and On-Body Interaction

Wearable tangible interfaces leverage body anchoring and passive haptics to provide stable, always-available input without requiring users to continuously grasp external devices. Simple analog components such as sliders, knobs, and dials can be especially effective in MR because they provide immediate tactile structure with relatively low hardware complexity [14]. By contrast, active haptic systems such as NormalTouch and TextureTouch [5] explore richer surface feedback, but their actuation and power requirements make them less suitable for lightweight, continuously wearable configurations.

Among on-body tangible systems, ARm Haptics [16] is the closest precedent to TactiFlow. It demonstrated that forearm-mounted controls can benefit from body anchoring and support precise interaction in AR. At the same time, it also highlighted a core challenge of on-body tangibles: linking physical modules to virtual targets can become effortful when interaction depends on sustained physical-virtual alignment. In ARm Haptics, users needed to raise the arm and visually align modules with corresponding virtual elements, making the process slow and fatiguing in multi-parameter workflows.

More broadly, wearable tangibles make a familiar HCI trade-off more acute. Because body space is limited, only a small number of physical controls can be worn comfortably at once. This means wearable systems must not only support precise manipulation, but also provide efficient ways to rebind those controls as tasks evolve. TactiFlow builds on prior on-body interaction work by supporting multiple coexisting forearm modules and by exploring rebinding techniques that avoid marker-based workflows and do not require continuous alignment during manipulation.

2.3 Linking and Rebinding in MR Interfaces

A persistent limitation in tangible and MR interfaces is that physical controls are often treated as statically mapped: a slider, token, or proxy is bound to one virtual function unless it is manually repositioned, physically reconfigured, or reassigned through an auxiliary selection sequence [11, 21, 46]. In practice, however, many immersive analytics tasks require users to move repeatedly across a larger virtual parameter space than can be directly represented by available physical controls.

Prior systems have explored related ideas through spatial coupling, token placement, gaze or ray-based selection, and indirect mode-switching mechanisms [18, 34, 37, 45]. These approaches demonstrate different ways of connecting input to virtual content, but few treat linking itself as a first-class interaction technique to be designed and evaluated. This is particularly true for wearable tangible systems, where rebinding is not a minor setup action but a recurring part of normal use whenever a small number of worn controls must serve many parameters.

This gap is especially relevant in immersive analytics. Frameworks such as the Immersive Analytics Toolkit identify filtering, linking, and manipulation as core analytic operations [10], and surveys point to the continuing need for interaction techniques that are both expressive and ergonomically sustainable in immersive settings [12, 33]. Yet relatively little work has examined how wearable physical controls should be rapidly and repeatedly rebound to virtual parameters during analytic tasks [38, 40].

TactiFlow contributes to this underexplored space by examining dynamic rebinding of on-body controls as an important MR interaction problem and by comparing three embodied linking techniques (Head-Tilt, Gesture-Select, and computer-vision-assisted Physical-Alignment) that reflect different trade-offs among low-motion targeting, familiar hand-based selection, and spatial coupling. In doing so, the paper shifts attention from tangibility alone to the broader question of how scarce wearable controls can remain usable across larger and changing parameter sets.

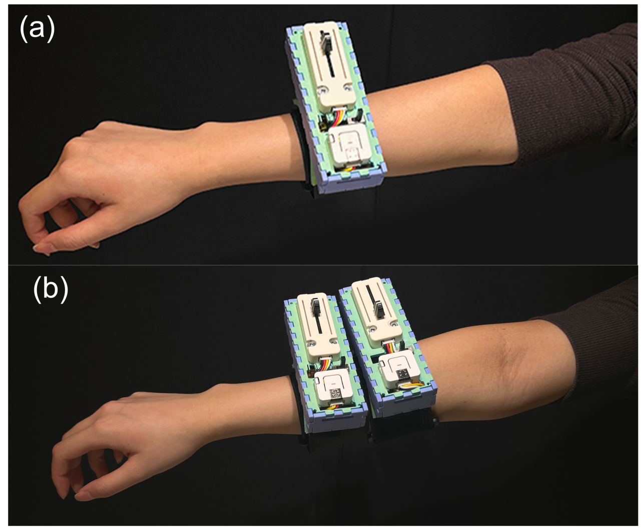

Figure 1: Forearm-mounted baseplate with interlocking module attachments. Modules snap into the baseplate's shared connector geometry, allowing users to add, remove, or reposition modules during use. The curved form factor distributes weight across the arm and supports stable on-body access.

3 TACTIFLOW DESIGN

TactiFlow is a forearm-worn tangible interface designed to investigate an important challenge in wearable MR interaction: how a small number of on-body physical controls can be dynamically rebound to a larger set of virtual parameters. The system consists of compact slider-and-button modules that attach to a body-worn baseplate (Figure 1), allowing users to physically manipulate parameters while relinking modules as task demands change. In this way, TactiFlow supports tangible parameter control while treating rebinding as a first-class interaction operation. Our design goal was to preserve the fine-grained stability of passive haptics while avoiding workflows that require a dedicated physical control for every virtual parameter.

3.1 Interaction Design

TactiFlow enables a user to link a forearm-worn module to a virtual parameter, manipulate that parameter through the module's slider, then release and relink the module as needed. This interaction follows a repeatable four-step cycle (Figure 2):

(1) **Target a parameter.** A candidate virtual parameter is highlighted using one of three linking techniques.
(2) **Confirm the link.** Pressing the module's button binds that physical module to the highlighted parameter, and the parameter's visual state updates to indicate active control.

(3) **Manipulate the parameter.** Moving the module's slider continuously updates the linked virtual parameter and its visualization.
(4) **Release and rebind.** A double press unlinks the module, allowing it to be rebound to another parameter.

This cycle keeps mappings explicit, reversible, and lightweight, which is especially important when a small number of wearable controls must serve a larger and changing parameter set.

A key design question is how users should specify which parameter a module should control. Prior forearm-mounted systems such as ARm Haptics [16] demonstrate the value of body-anchored control, but their linking workflows can require users to raise the arm and maintain physical-virtual alignment, making repeated rebinding slow and effortful in multi-parameter tasks. To explore alternatives, we designed three embodied rebinding techniques that represent distinct approaches to on-body control assignment: head-mediated targeting, hand-mediated selection, and forearm-mediated spatial coupling (Figure 3):

Head-Tilt (head-mediated targeting). Head-Tilt uses small head movements to target a virtual parameter while the forearm can remain in a relaxed position. A ray originating from the headset's center-eye position is continuously cast into the scene. As the user subtly reorients their head, the ray moves across virtual sliders; when it intersects a parameter, that parameter highlights in yellow to indicate link eligibility. Pressing the module button confirms the link. This technique adapts gaze-inspired targeting to head motion, making it usable on devices without reliable eye tracking while minimizing upper-arm involvement during repeated rebinding.

Gesture-Select (hand-mediated selection with tangible confirmation). Gesture-Select combines familiar hand-tracked pointing with on-device confirmation. The user performs a pinch gesture to activate a hand-anchored ray pointer, and the intersected parameter highlights in yellow. Unlike Head-Tilt, the pinch both selects and locks the highlight, allowing the user to lower or relax the arm before committing. A second pinch on the same parameter deselects it. The link is established only when the user presses the wearable module's button. By separating target selection from commitment, this technique combines flexible in-air pointing with explicit tangible confirmation.

Physical-Alignment (forearm-mediated spatial coupling). Physical-Alignment grounds rebinding in approximate spatial correspondence between the forearm-mounted module and the virtual interface. The user raises the forearm and positions the module beneath the desired virtual slider. As the module moves through space, the system detects its approximate screen-aligned region and highlights the corresponding virtual parameter. Pressing the module button confirms the link. Importantly, spatial alignment is required only during the linking step; once the module is linked, the arm can be lowered and manipulation continues from a resting posture. This technique preserves an intuitively embodied mapping between module position and parameter assignment while avoiding the need to maintain alignment during subsequent manipulation.

Taken together, these three techniques define a compact embodied design space for dynamic rebinding in on-body MR interaction. They differ in motor demand, perceptual focus, and spatial grounding, allowing us to examine how rebinding technique, rather than manipulation modality alone, shapes usability in immersive analytics.

3.2 Example Application: Real-Estate Data Exploration

To study TactiFlow in a task that requires both repeated rebinding and fine-grained parameter adjustment, we integrated it into an MR real-estate exploration application. Users explore a map of a large North American metropolitan area and adjust multiple filters (including price, size, number of bedrooms, number of bathrooms, and days on market) each represented as a virtual slider. The application includes: (1) linked sliders that update filters in real time, (2) a heatmap encoding the density of available property listings across neighborhoods, (3) parameter labels showing current values, and (4) visual states indicating candidate, active, and previously used parameters.

Heatmap color intensity reflects listing concentration, with deeper red indicating neighborhoods with higher densities of available homes. During the study, participants manipulated parameters to shape this visualization, often working toward target patterns in specific regions. We selected this task context because it requires participants to repeatedly move between parameters while also making fine-grained adjustments, thereby foregrounding both the manipulation and rebinding demands that TactiFlow is intended to support. Supplementary Figure S1 illustrates TactiFlow in use within the real-estate scenario, showing how the forearm-mounted modules and virtual sliders operate together during live parameter control.

4 SYSTEM IMPLEMENTATION

TactiFlow was implemented as a modular forearm-worn MR system designed to support repeated rebinding of a small set of wearable controls to virtual parameters. The implementation combines detachable tangible modules, a forearm-mounted baseplate, embedded firmware, and a Unity-based MR application running on Meta Quest 3. This section summarizes the physical design, hardware components, communication architecture, and mechanisms used to support reliable behavior during repeated rebinding.

4.1 Case Design and Fabrication

Each wearable module is housed in a compact 3D-printed enclosure that snaps onto a curved forearm baseplate through a shared connector geometry. The baseplate is secured with adjustable Velcro straps and distributes module weight along the forearm, supporting stable on-body access in both seated and standing use.

The mechanical design prioritizes modularity, replicability, and body conformance. The enclosure and baseplate were modelled in OpenSCAD [26] and Autodesk Fusion [2], then fabricated in PLA to support durability and rapid iteration. All modules use the same snap-fit interface, allowing them to be attached, removed, or repositioned without tools. The curved baseplate keeps the modules close to the forearm surface, reducing wrist torque during use.

Although our evaluation focuses on a slider-and-button module, the mounting and communication interface was designed to accommodate additional module types in future work, such as rotary

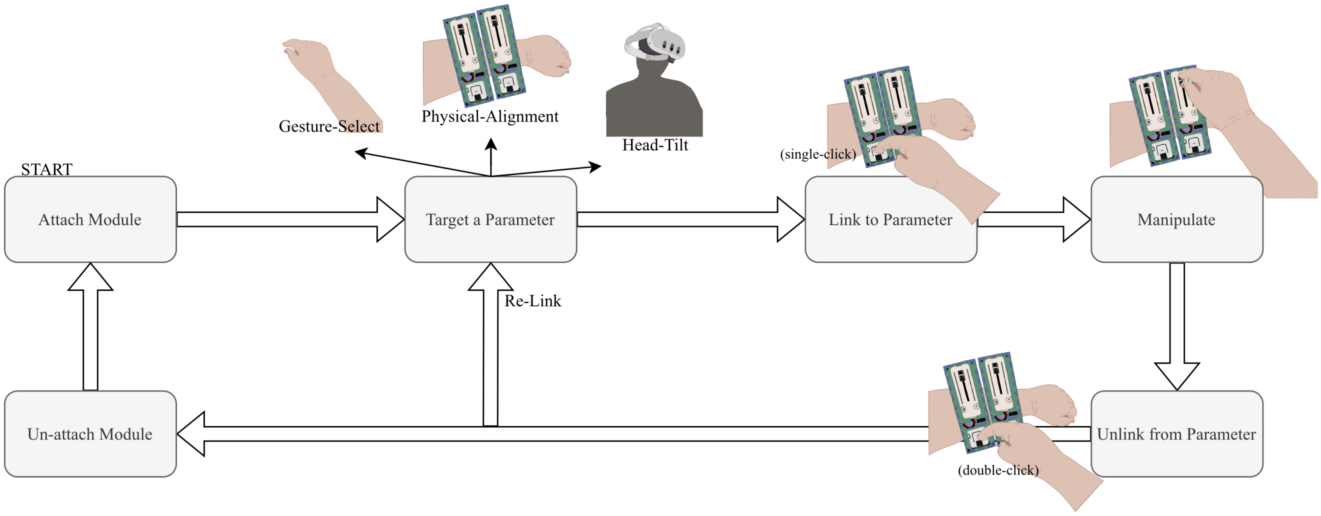

Figure 2: TactiFlow interaction flow. Users target a parameter, confirm the link on the wearable module, manipulate the parameter through the physical slider, and release and rebind the module as tasks evolve.

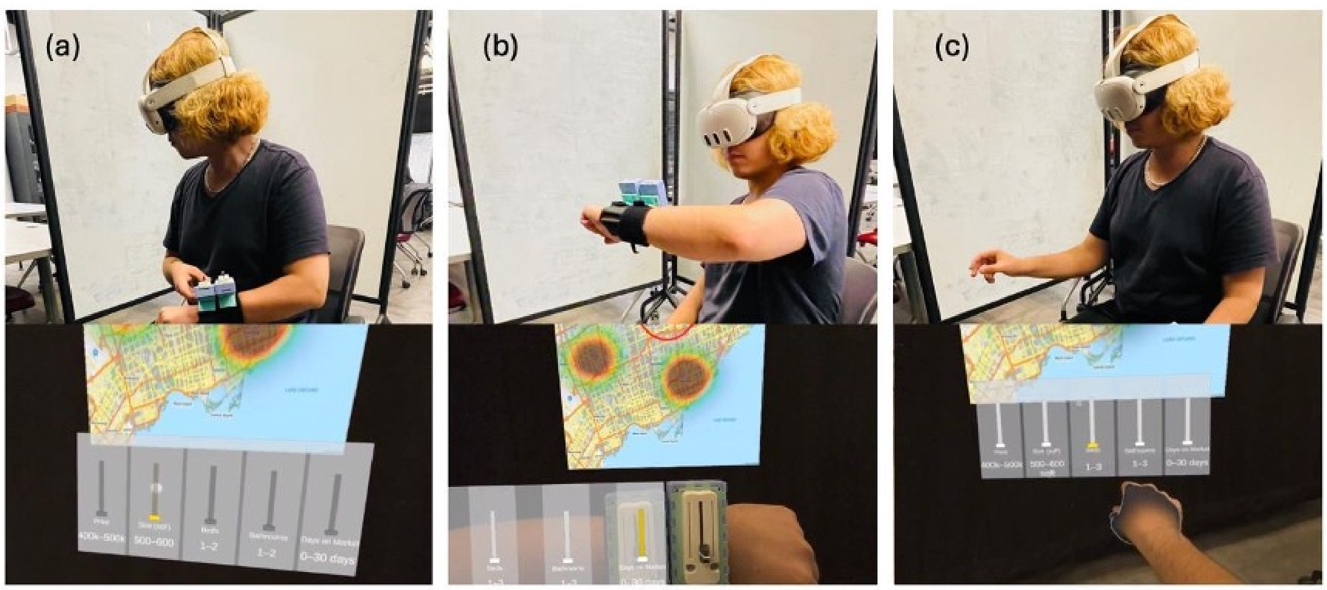

Figure 3: Three rebinding techniques for assigning modules to virtual parameters in MR. (a) Head-Tilt uses head-directed targeting with on-device confirmation. (b) Physical-Alignment uses approximate spatial correspondence between the forearm module and the virtual interface. (c) Gesture-Select combines hand-tracked pointing with tangible confirmation.

encoders, knobs, or thumb joysticks, without requiring redesign of the baseplate or rebinding workflow.

4.2 Hardware

Each module integrates commercially available M5Stack components: (1) an M5Stack ATOM S3 Lite microcontroller for Wi-Fi communication and event processing, (2) an M5Stack Fader Unit providing a linear analog slider with a passive tactile midpoint and LED indicators, (3) a 2000 mAh 3.7 V lithium-ion rechargeable battery, (4) an on-device tactile button used for link confirmation and unlinking, and (5) an embedded hardware power switch (Supplementary Figure S2).

Firmware was implemented in C++ using the Arduino toolchain. Each module streams slider values and button events to the MR application over Wi-Fi at interactive rates.

Each fully assembled module, including enclosure, electronics, and battery, weighs approximately 115 g. While the prototype was not miniaturized for consumer deployment, it was sufficient for the mid-duration study sessions reported here and did not appear to prevent normal forearm movement during interaction.

The immersive environment runs on a Meta Quest 3 using Unity 6.1, which manages linking logic, visual feedback, parameter state transitions, and synchronization with the wearable modules.

4.3 System Architecture and Communication

Figure 4 illustrates the end-to-end data path from physical input to virtual parameter update. Each wearable module maintains a dedicated Wi-Fi socket connection to the Unity application, which processes incoming events through a thread-safe queue so that multiple modules can remain active concurrently.

Within the MR application, each virtual parameter is represented using a small set of mutually exclusive states:

- **Default:** not currently targeted.
- **Candidate:** highlighted as a potential link target.
- **Active:** currently controlled by a specific module.
- **Used:** previously controlled and shown with a faded encoding.

To avoid ambiguous mappings, the system enforces strict exclusivity: each module can control only one parameter at a time, and each parameter can be controlled by only one module.

Linking is implemented as an explicit intentional action. When the user presses a module button, the system binds that module to the currently highlighted virtual parameter. This explicit confirmation step keeps control relationships legible and reversible, which is especially important when a limited number of wearable modules must serve a larger set of virtual controls.

To preserve responsiveness, the implementation disables Nagle's algorithm (TCP_NODELAY) and uses compact event messages to reduce transmission overhead. Under study conditions, end-to-end latency remained below 60 ms, which was sufficient for responsive parameter adjustment in our study.

Several safeguards were added to maintain stable rebinding behavior. Input debouncing distinguishes single-press confirmation from double-press unlinking. Ownership validation prevents multiple modules from claiming the same parameter. Disconnect handling releases active links when a module loses connection, preventing stale mappings. Update thresholding reduces transmission of slider changes that do not meaningfully affect the controlled parameter. Together, these mechanisms support predictable system behavior across all three rebinding techniques.

4.4 Handling State Consistency

Because each module uses a passive, non-actuated slider, its physical position does not automatically match the value of a newly linked virtual parameter. Without additional handling, rebinding could therefore produce sudden discontinuities when control is transferred from one parameter to another.

To address this, TactiFlow uses a deadband soft-takeover strategy. After a module is linked to a new parameter, the virtual value remains unchanged until the physical slider crosses the parameter's current value. Only after this crossover does continuous control resume. This approach prevents abrupt jumps, preserves user expectations, and supports repeated rebinding without destabilizing the interaction.

5 EVALUATION

We conducted a within-subjects evaluation of TactiFlow in an MR real-estate analytics scenario. The evaluation was structured around two tasks with different roles in the paper. Task 1 served as a supporting validation step, examining whether the wearable slider module provides an effective substrate for parameter manipulation when linking is removed. Task 2, which constitutes the main study, examined how a small number of wearable controls can be dynamically rebound to many virtual parameters through different embodied linking techniques. Both tasks were grounded in the same application context described in Section 3.2 so that they reflected repeated parameter changes, coordinated filter adjustment, and other patterns typical of immersive analytics workflows.

5.1 Study Design

Each 70-90 minute session followed a standardized sequence consisting of introduction, tutorial, practice, counterbalanced experimental blocks, and post-study questionnaires and interviews. This structure was designed to ensure that participants understood each interaction technique before logged trials began and to reduce learning asymmetries across conditions. An overview of the study is provided in Table 1.

This design intentionally assigned different purposes to the two tasks. Task 1 isolated manipulation by removing linking overhead. Task 2 evaluated the full link-manipulate-unlink-relink cycle and served as the paper's main empirical comparison.

5.2 Participants

We recruited 18 participants (9 women, 9 men). Age was distributed across multiple ranges: 8 participants were 18-24, 7 were 25-34, 1 was 35-44, 1 was 45-54, and 1 was 65 or older. All sessions were conducted individually. Participants provided informed consent and received a $15 Amazon gift card.

Sixteen participants were right-handed and two were left-handed. Participants used their dominant hand for slider interaction.

Participants reported mixed familiarity with MR/VR systems on a 7-point self-report scale (4 rated 1, 6 rated 2, 2 rated 3, 2 rated 4, 3 rated 5, and 1 rated 6). Prior use of MR/VR headsets in personal or professional contexts was generally limited (10 rated 1, 5 rated 2, 2 rated 4, and 1 rated 6 on a 7-point scale), and headset use frequency was low overall, with 17 participants reporting rare use and 1 reporting occasional use.

This sample size is consistent with prior within-subjects evaluations of MR and tangible interaction techniques [6, 27, 39]. To assess sensitivity, we conducted a power-based design check assuming $\alpha = 0.05$ and power = 0.80. For Task 1 (two conditions), the design was sensitive to effects of approximately Cohen's $d = 0.70$ or larger. For Task 2 (three conditions), the design was sensitive to effects of approximately partial $\eta^2 = 0.16$. We report effect sizes and confidence intervals alongside inferential statistics to support

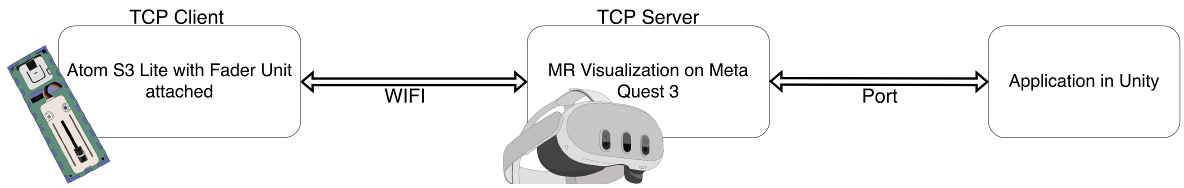

Figure 4: System architecture for TactiFlow. Modules communicate wirelessly with Meta Quest 3 using a lightweight TCP protocol. Unity manages rebinding logic, parameter state transitions, visual feedback, and synchronization with the wearable devices.

Table 1: Overview of evaluation tasks, conditions, and procedures.

Task	Conditions	Task description	Role in study	Counterbalancing
Task 1 – Manipulation validation (pre-linked)	1) Physical slider (M-Phys) 2) In-air pinch-drag (M-Air)	Adjust two parameters (Min Price and Min Bedrooms) to maximize the heatmap's red coverage (property density)	Validate the wearable tangible module as a manipulation substrate without rebinding overhead	AB/BA
Task 2 – Rebinding comparison	1) Head-Tilt 2) Physical-Alignment 3) Gesture-Select	Two rebinding cycles: link to two parameters, manipulate both, unlink, then relink to two different parameters and manipulate (4 parameters total per technique)	Compare the speed, reliability, workload, and user experience of embodied rebinding strategies	Williams Latin Square

transparent interpretation. We did not analyze age or prior MR experience as inferential factors because the study was not powered for subgroup comparisons.

5.3 Procedure

After consent and demographics, participants completed a structured tutorial introducing all manipulation and rebinding techniques. Each technique was followed by two unlogged practice trials to ensure participants understood the mechanics before logged trials began, although some additional learning may still have occurred during the study, particularly for the less familiar rebinding techniques.

In Task 1, participants completed one trial with M-Phys and one trial with M-Air. In the M-Phys condition, the experimenter pre-linked the wearable module to the relevant parameters before the trial began, eliminating rebinding overhead. In the M-Air condition, participants manipulated the same parameters using in-air pinch-drag interaction. In both conditions, the task was to adjust the filters so as to maximize heatmap density rather than to match fixed target values. This task was designed only to validate manipulation performance when the control mapping was already established.

In Task 2, participants completed the main rebinding study. For each linking technique, they performed two rebinding cycles: (1) link to two parameters, (2) manipulate both to reach specified target values, (3) unlink both, (4) relink to two different parameters, and (5) manipulate those parameters. This yielded four parameter assignments per technique. After the rebinding cycles, participants completed a multi-parameter scenario requiring coordinated filter adjustment. Condition order was counterbalanced using a Williams Latin Square.

After all conditions, participants completed a short NASA-TLX, ease-of-use ratings, preference ratings, and open-ended feedback about clarity, strengths, weaknesses, and perceived effort across techniques.

5.4 Task Design

The tasks were designed to preserve the structure of immersive analytics work while allowing controlled comparison across conditions. Both tasks used the same real-estate exploration scenario introduced in Section 3.2, in which participants adjusted filters such as price, size, and bedroom count while observing the resulting distribution of matching properties.

Task 1 focused narrowly on manipulation. By using pre-linked modules, it removed rebinding from the interaction loop and allowed us to assess how efficiently participants could make fine-grained parameter adjustments once control mappings were already established. The task of maximizing heatmap density reflects common analytic behavior such as threshold tuning, incremental filter refinement, and repeated adjustment while monitoring immediate visual feedback. We note that this was an open-ended optimization task intended to validate manipulation under a realistic analytic workflow, rather than to benchmark exact target-matching performance.

Task 2 examined the full interaction cycle supported by TactiFlow: link, manipulate, unlink, and relink. Each technique required participants to repeatedly assign a limited number of wearable controls to different parameters, then use those controls to reach target values and complete a broader multi-parameter filtering task. This structure was chosen because it foregrounds the paper's main problem: how rebinding technique affects usability when a small number of on-body controls must support a larger virtual parameter space. All Task 2 conditions were evaluated in the same seated context to maintain consistency across techniques, though this choice likely constrained movement freedom for Physical-Alignment more than for the other techniques.

Using the same application context across both tasks helped preserve task continuity while allowing the study to separate manipulation validation from the main rebinding comparison.

5.5 Measures

We collected objective performance measures, subjective ratings, and qualitative feedback. These measures were selected to capture both efficiency and user experience, with the primary emphasis on evaluating rebinding performance in Task 2.

5.5.1 *Objective measures.*

- **Time-to-target (Task 1):** time from trial onset until participants indicated they were satisfied with their heatmap optimization, used as a measure of manipulation efficiency.
- **Number of adjustments (Task 1):** count of slider changes, used as a proxy for control stability and corrective movement.
- **Time-to-link (Task 2):** duration from the start of a linking attempt to successful link establishment.
- **Relinking time (Task 2):** duration required to unlink and establish a new link to a different parameter.
- **Linking errors (Task 2):** failed or incorrect linking attempts, such as confirming when no valid target was active.
- **Scenario completion time (Task 2):** total duration required to complete the broader multi-parameter task.

5.5.2 *Subjective measures.*

- **Ease-of-use ratings:** 7-point Likert ratings assessing clarity, controllability, and overall ease of each condition.
- **Workload:** NASA-TLX short form collected after each condition, including effort, physical demand, and frustration.
- **Post-study summary ratings:** overall preference rankings and perceived suitability for sustained analytic use.

5.5.3 *Qualitative measures.*

Participants provided open-ended feedback after each condition and at the end of the study. They commented on clarity of the interaction sequence, perceived strengths and weaknesses, sources of confusion or effort, and reasons for their preferences. These responses were used to contextualize the quantitative findings and surface practical design considerations for wearable rebinding in immersive analytics.

5.6 Hypotheses

Because the main contribution of the paper concerns rebinding rather than manipulation alone, our hypotheses primarily focus on differences among linking techniques, with one supporting hypothesis for Task 1 validation.

- **H1 (Manipulation validation):** When linking overhead is removed, wearable physical sliders will support more efficient fine-grained parameter adjustment than in-air pinch-drag, reflected in shorter time-to-target and fewer corrective adjustments.
- **H2 (Rebinding efficiency):** The three embodied rebinding techniques will differ significantly in linking and relinking performance, reflecting trade-offs among head-mediated targeting, hand-mediated selection, and spatial coupling.
- **H3 (Rebinding workload and experience):** The three rebinding techniques will differ in perceived workload and ease of use, with lower-motion techniques expected to reduce physical effort and spatially grounded techniques expected to influence perceived intuitiveness.
- **H4 (Overall usability of rebinding techniques):** Participants' preferences will reflect trade-offs among speed, effort, and intuitiveness across the three rebinding techniques.

6 RESULTS

We analyzed objective performance, subjective ratings, and qualitative feedback across both tasks. Because Task 1 served only as a supporting validation step for the wearable manipulation substrate, we report those results briefly. Our main analysis focuses on Task 2, which compares the three rebinding techniques. Statistical assumptions were evaluated with Shapiro–Wilk tests; parametric tests (paired t-tests, repeated-measures ANOVA) were used when assumptions were met, and non-parametric alternatives (Wilcoxon, Friedman) otherwise. Holm correction was applied to post-hoc comparisons.

NASA-TLX internal consistency varied across conditions (M-Air $\alpha = 0.784$; M-Phys $\alpha = 0.349$; Head-Tilt $\alpha = 0.664$; Physical-Alignment $\alpha = 0.667$; Gesture-Select $\alpha = 0.654$). We therefore interpret TLX composite values cautiously and emphasize relative differences rather than absolute magnitudes.

6.1 Task 1: Manipulation Validation

Task 1 examined whether the wearable physical slider provided an effective manipulation substrate once linking overhead was removed.

6.1.1 *Performance.*

Participants completed parameter adjustment significantly faster with the physical slider (M-Phys) than with in-air pinch-drag (M-Air) (Supplementary Figure S3a). Median time-to-target was 35 s for M-Phys and 52.5 s for M-Air ($p = 0.023$). In contrast, the number of adjustments did not differ significantly ($p = 0.794$; Supplementary Figure S3b), suggesting that both modalities supported similar patterns of incremental correction once interaction was underway.

6.1.2 *Subjective ratings and preference.*

Ease-of-use ratings favored the physical slider ($p = 0.010$; Supplementary Figure S4b), while NASA-TLX composite workload did not differ significantly between conditions (Supplementary Figure S4a). Participants also strongly preferred M-Phys overall, with 83% ranking it first ($p < 0.005$; Supplementary Figure S5). In qualitative feedback, participants often described the physical slider as easier to control and more reliable than pinch-drag. As one participant noted, the virtual slider "was not easy to grab and not as accurate as [the] physical slider."

Taken together, Task 1 supports the wearable module as a credible manipulation substrate for the main rebinding comparison.

6.2 Task 2: Rebinding Techniques

Task 2 compared the three embodied rebinding techniques: Head-Tilt, Gesture-Select, and Physical-Alignment.

6.2.1 Temporal metrics.

Linking time differed significantly across techniques ($\chi^2(2) = 19.803$, $p < 0.001$, Kendall's $W = 0.550$). As shown in Figure 5a, Head-Tilt was fastest (median 10 s), Gesture-Select was intermediate (17.5 s), and Physical-Alignment was slowest (43.5 s). This ordering was also visible in the full distributions (Figure 6), where Head-Tilt showed consistently short linking times across participants and Physical-Alignment showed substantially longer and more variable performance.

Relinking time showed an even stronger condition effect ($\chi^2(2) = 29.600$, $p < 0.001$, Kendall's $W = 0.822$; Figure 5b), again favoring Head-Tilt over the other techniques. Gesture-Select remained intermediate, while Physical-Alignment was consistently slowest.

These results indicate that the overall differences among techniques were driven primarily by rebinding overhead itself. Because the slider-based parameter manipulation after successful binding was held constant across conditions, the advantage of Head-Tilt is best explained by faster linking and relinking, together with reduced recovery from failed assignments, rather than by differences in post-link manipulation.

6.2.2 Error rates.

Error rates also differed significantly across techniques. For linking errors, the Friedman test showed a reliable condition effect ($\chi^2(2) = 14.271$, $p < 0.001$, Kendall's $W = 0.396$). Holm-corrected pairwise comparisons were significant for all three contrasts: Head-Tilt vs. Physical-Alignment ($p = 0.002$), Head-Tilt vs. Gesture-Select ($p = 0.028$), and Gesture-Select vs. Physical-Alignment ($p = 0.028$).

Relinking errors showed the same ordering, with an even larger omnibus effect ($\chi^2(2) = 18.321$, $p < 0.001$, Kendall's $W = 0.509$). Again, all Holm-corrected pairwise comparisons were significant: Head-Tilt vs. Physical-Alignment ($p = 0.002$), Head-Tilt vs. Gesture-Select ($p = 0.017$), and Gesture-Select vs. Physical-Alignment ($p = 0.008$).

Across both error measures, Head-Tilt produced the fewest errors, Gesture-Select was intermediate, and Physical-Alignment produced the most. This pattern reinforces that performance differences in Task 2 were associated not only with faster rebinding, but also with fewer failed assignments and less error recovery.

6.2.3 Workload and ease of use.

Composite NASA-TLX workload differed significantly across rebinding techniques ($F = 24.069$, $p < 0.001$, partial $\eta^2 = 0.586$; Figure 7a). Physical-Alignment produced the highest workload, while Head-Tilt and Gesture-Select were substantially lower and more similar to one another. NASA-TLX subscale profiles (Figure 8) showed that Physical-Alignment was associated with elevated mental demand, physical demand, effort, and frustration relative to the other techniques.

Ease-of-use ratings followed a similar pattern (Figure 7b): Head-Tilt received the highest ratings overall, followed by Gesture-Select, while Physical-Alignment was rated lowest. Head-Tilt was also rated easier to use than Gesture-Select.

6.2.4 Preferences and qualitative feedback.

Preference rankings were consistent with the quantitative results (Figure 9). Head-Tilt was ranked first by most participants, whereas Physical-Alignment was consistently ranked last. In qualitative feedback, participants frequently described Head-Tilt as fast, direct, and easy to repeat. Gesture-Select was often viewed as familiar and understandable, though some participants reported occasional inconsistency in pinch recognition. Physical-Alignment was commonly described as effortful and slower to execute, especially when repeated relinking was required.

6.2.5 Individual differences.

Per-participant trajectories (Figure 10) showed notable between-participant variability, but the relative ordering of techniques remained broadly consistent. These patterns suggest that the observed effects were not driven solely by a small subset of participants, but instead reflected technique-dependent differences across the sample.

7 DISCUSSION

This study examined TactiFlow as a wearable tangible MR system designed around an important problem: how a small number of on-body controls can be rebound to a larger set of virtual parameters. Across both tasks, the findings show that wearable tangibles can provide an effective substrate for parameter manipulation, but more importantly, that the design of the rebinding mechanism has an important influence on speed, reliability, workload, and overall usability. In other words, for rebindable on-body interfaces, linking is not merely a secondary setup step; it is an important part of the interaction.

7.1 Task 1 as Supporting Validation

Task 1 was included to validate the wearable slider module as a plausible manipulation substrate before comparing rebinding techniques. Consistent with prior work on tangible interaction in MR and VR [17, 32, 41], physical sliders supported faster parameter adjustment than in-air pinch-drag and were rated easier to use, while the number of corrective adjustments remained comparable across modalities. This suggests that the benefit of the wearable slider lies less in changing the structure of fine-grained correction and more in improving the fluency of parameter adjustment once control has been established.

We therefore interpret Task 1 as confirming that the on-body module provides a reasonable tangible basis for the paper's main question. At the same time, we note that this task used an open-ended optimization procedure rather than exact target matching, and should therefore be understood as a validation of manipulation under a realistic analytic workflow rather than as a definitive benchmark of parameter-adjustment accuracy.

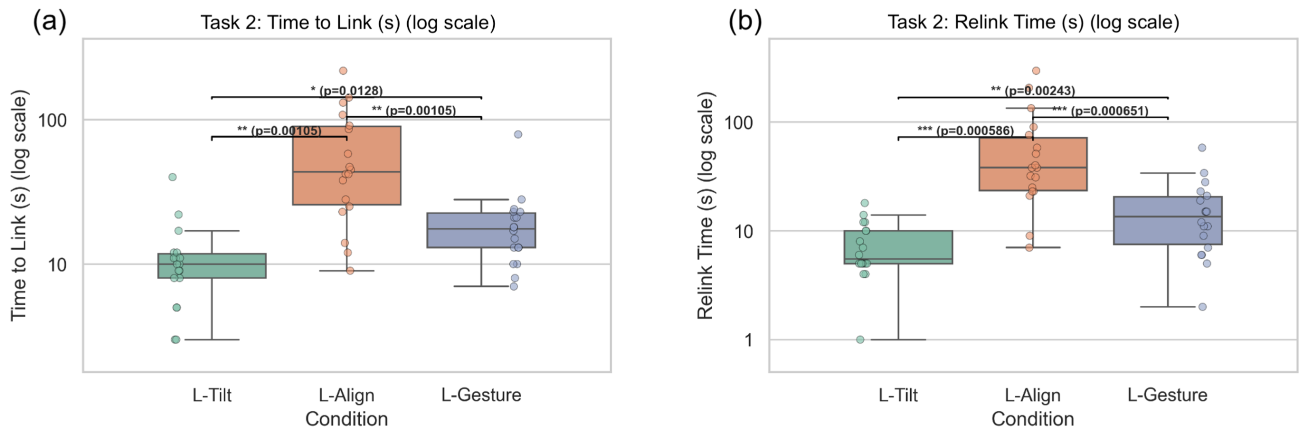

Figure 5: Task 2 rebinding performance. (a) Time-to-link across Head-Tilt, Gesture-Select, and Physical-Alignment. (b) Time-to-relink across the three rebinding techniques.

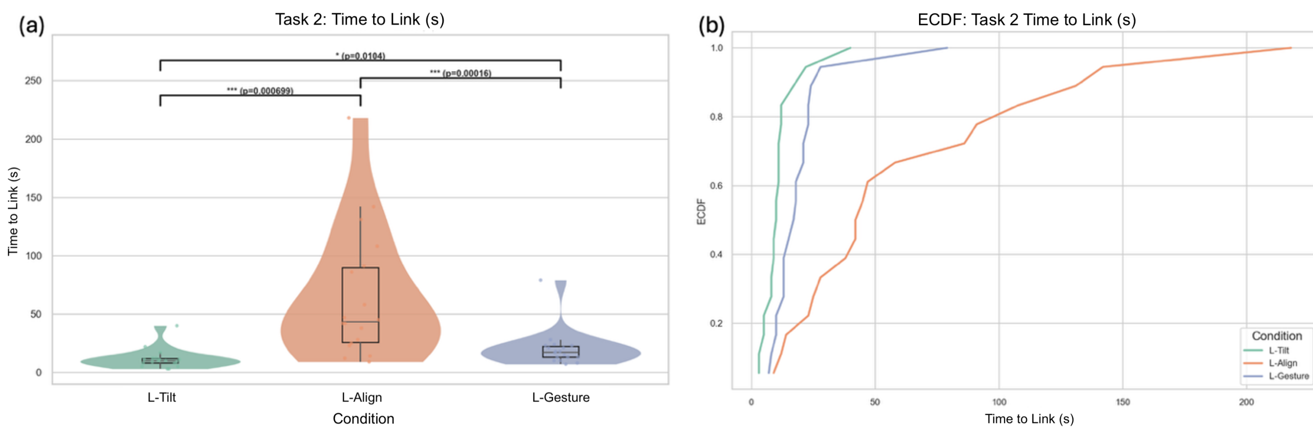

Figure 6: Distributions of Task 2 linking times. (a) Raincloud plots showing the spread of link times across participants for each rebinding technique. (b) Empirical cumulative distribution functions (ECDFs) showing relative completion rates across techniques.

7.2 Rebinding as the Main Interaction Contribution

The main contribution of the study comes from Task 2. The three rebinding techniques differed substantially in speed, reliability, workload, and preference, showing that the usability of on-body tangible controls depends strongly on how rebinding is implemented.

Head-Tilt performed best overall. It was the fastest, produced the fewest errors, and received the strongest subjective ratings. Participants frequently described it as direct and easy to repeat. One reason may be that Head-Tilt couples a low-amplitude targeting action with an explicit on-device confirmation step, allowing rapid rebinding without requiring sustained arm elevation or high manual precision. More broadly, this result suggests that head-mediated targeting can be highly effective when the task is not continuous navigation or pointing, but quick reassignment of control.

Gesture-Select provided a useful middle ground. It benefited from the familiarity of hand-based pointing, and several participants reported that it became smoother with practice. At the same time, it inherited some instability from pinch recognition, which intermittently disrupted flow. Gesture-Select therefore appears viable as a more familiar rebinding technique, though its performance remains tied to the robustness of the hand-tracking pipeline.

Physical-Alignment was the slowest and most demanding technique in our study context. Although it offers an intuitively embodied mapping between module position and parameter assignment, this spatial logic alone did not translate into efficient use. Even without requiring continuous alignment during manipulation, the need to raise, position, and stabilize the forearm during the linking step increased effort and reduced reliability, especially under the seated study setup used here. This is an important result: embodied spatial coupling may appear natural in principle, but its practical

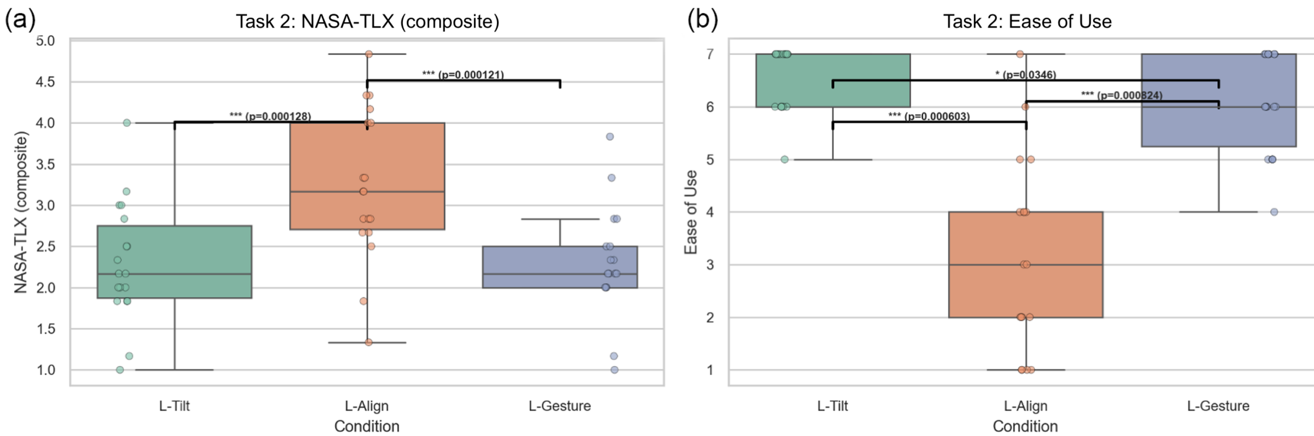

Figure 7: Subjective ratings for Task 2 rebinding techniques. (a) NASA-TLX composite workload across Head-Tilt, Gesture-Select, and Physical-Alignment. (b) Ease-of-use ratings for the three rebinding techniques.

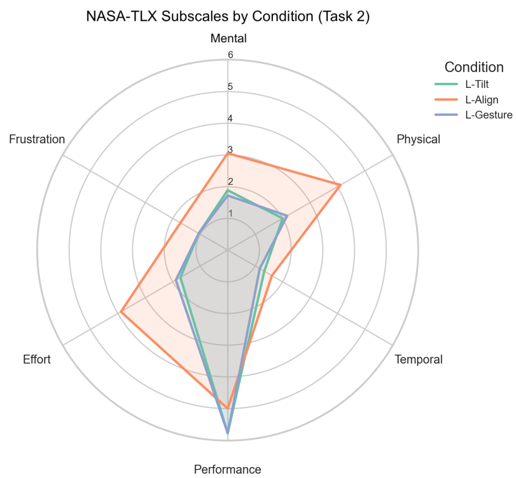

Figure 8: NASA-TLX subscale profiles for the Task 2 rebinding techniques, including mental demand, physical demand, effort, perceived performance, and frustration.

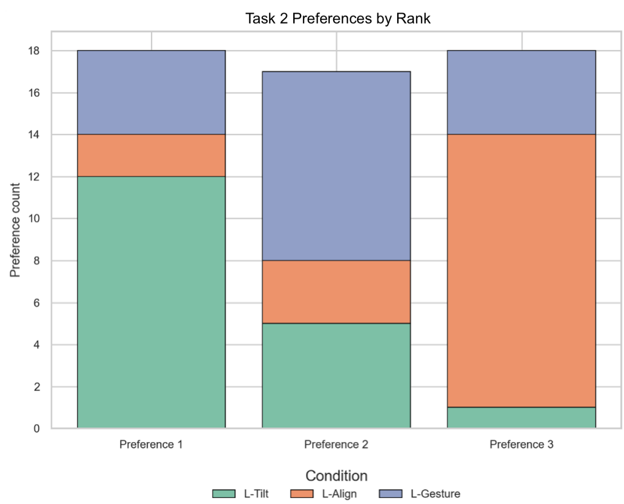

Figure 9: Preference rankings for the Task 2 rebinding techniques. Head-Tilt was most frequently ranked first, whereas Physical-Alignment was most frequently ranked last.

value depends heavily on posture, movement freedom, and sensing stability.

Taken together, these findings shift the contribution of TactiFlow away from wearable tangibility alone and toward a more specific claim: dynamic rebinding is an important design challenge for on-body MR controls, and different rebinding strategies produce materially different usability outcomes.

7.3 Design Implications

The results suggest several design implications for future rebindable on-body MR systems. First, rebinding should be treated as a primary interaction problem rather than as occasional setup. When a small number of wearable controls must serve many parameters, rebinding becomes part of normal interaction and should be designed and evaluated with the same care as manipulation itself. Second, low-motion targeting can outperform more spatially grounded approaches. Head-Tilt showed that rebinding can be fast and reliable without requiring large arm movement or precise manual pointing, suggesting that for repeated rebinding tasks, minimizing movement overhead may be more important than maximizing embodied spatial correspondence.

Third, spatial coupling is not sufficient on its own. Physical-Alignment was intuitive in concept, but its practical performance was limited by posture demands and alignment sensitivity. Designers should therefore avoid assuming that spatially "natural" mappings will automatically lead to efficient rebinding. Fourth, explicit confirmation remains valuable. Across all three techniques, module-button confirmation made control assignment legible and

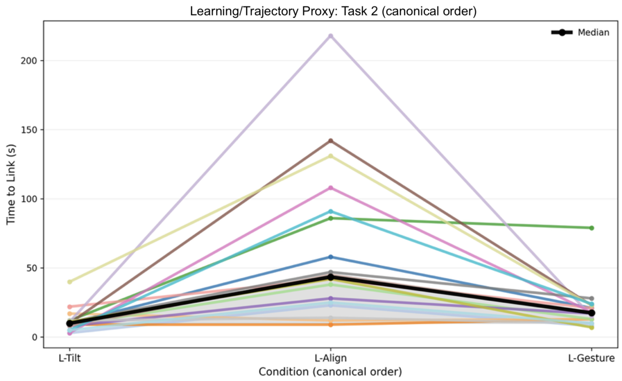

Figure 10: Per-participant performance trajectories across the three rebinding techniques. Each polyline connects one participant's performance for Head-Tilt, Gesture-Select, and Physical-Alignment.

reversible; in systems with scarce physical controls, explicit commitment helps prevent ambiguous or accidental mappings. Finally, rebinding techniques should be matched to context and user variability. Although Head-Tilt performed best overall, participant trajectories still showed individual differences. Supporting multiple rebinding strategies, or adapting them to posture, setting, or sensing conditions, may improve accessibility and robustness.

7.4 Limitations

This work should be interpreted in light of several limitations. First, the evaluation was conducted in a single immersive analytics scenario based on real-estate filtering. We selected this task because it required repeated rebinding and fine-grained parameter adjustment, but future work should examine whether the same rebinding patterns hold in other MR domains.

Second, the study examined short-term performance and immediate user impressions rather than long-term adaptation, repeated daily use, or sustained wearability. Although participants completed structured practice before logged trials, some additional learning may still have occurred during the study, particularly for the less familiar rebinding techniques. Accordingly, our claims center on comparative rebinding performance within a controlled study rather than long-term deployment readiness.

Third, although modularity is central to TactiFlow's design, the present study focused on one slider-and-button module type. We did not examine richer module ecologies, more complex module configurations, or how users might combine or exchange different module types over time.

Fourth, Physical-Alignment was evaluated in the seated study context used here. Its poorer performance should therefore be interpreted as evidence about that context, rather than as a universal rejection of spatially coupled rebinding. Standing, mobile, or collaborative settings may provide more movement freedom and could alter this trade-off.

Finally, our comparison was intentionally scoped to rebinding within wearable tangible MR interaction and did not attempt to benchmark all available MR input paradigms, such as commercial handheld controllers. The goal of the study was to understand how rebinding should work once a rebindable on-body tangible design has been chosen. Broader cross-paradigm comparisons remain a useful direction for future work, but were outside the scope of the present investigation.

8 FUTURE WORK

Several directions follow from these findings. A first priority is to study longer-term use, including how rebinding strategies evolve with practice and whether initial differences in effort, preference, or reliability persist over time.

A second direction is to expand TactiFlow beyond the single slider-and-button module evaluated here. Because the mounting and communication architecture is generic, future work could investigate richer module ecologies including knobs, joysticks, and other tangible controls, as well as how users choose among them for different analytic tasks.

A third direction is to examine context-sensitive rebinding more directly. Our results suggest that rebinding performance depends not only on interaction technique, but also on posture and available movement space. Future studies should therefore compare seated, standing, and mobile conditions, and investigate whether systems can adaptively recommend or switch rebinding strategies based on context.

Finally, future work could explore multi-user and collaborative scenarios in which on-body tangible modules support shared analytic tasks. In such settings, rebinding may become even more important as users shift attention across multiple views, parameters, and collaborative roles.

9 CONCLUSION

We presented TactiFlow, a modular forearm-worn tangible interface for mixed reality that supports dynamic rebinding of a small number of wearable controls to a larger set of virtual parameters. Through a within-subjects evaluation comprising two tasks, we first validated the wearable slider as a credible manipulation substrate and then compared three embodied rebinding techniques: Head-Tilt, Gesture-Select, and Physical-Alignment.

The results show that while wearable tangibility supports effective parameter manipulation, the design of the rebinding mechanism has a stronger influence on overall usability. Head-Tilt enabled the fastest and most reliable rebinding in our study context, Gesture-Select offered a familiar intermediate alternative, and Physical-Alignment revealed the costs that posture and spatial alignment can impose even when spatial coupling appears intuitive.

Taken together, these findings highlight the importance of rebinding design in wearable tangibles for MR and offer guidance for future on-body interfaces that must support many virtual parameters with a limited number of physical controls.

Acknowledgments

This work has been supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), and the Canada First Research Excellence Fund (CFREF) Bridging Divides research program. The authors would like to thank Aneesh Tarun and Afroza Sultana for their constructive feedback.

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