Blended Whiteboard: Physicality and Reconfigurability in Remote Mixed Reality Collaboration

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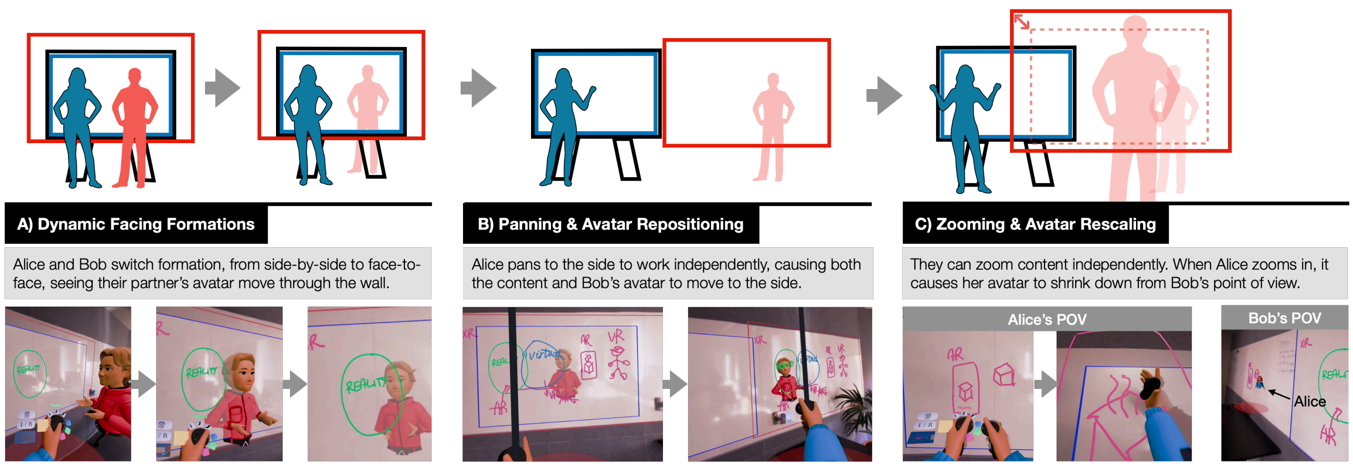

Figure 1: With Blended Whiteboard, remote users can collaborate across distributed physical whiteboards as if next to each other. But they can also dynamically reconfigure the whiteboard and avatar arrangements through Mixed Reality to suit the needs of their collaboration. They can switch between different collaboration styles—side-by-side and face-to-face (A)—and navigate an infinite whiteboard canvas as well as the avatar relations through panning (B) and zooming (C).

ABSTRACT

The whiteboard is essential for collaborative work. To preserve its physicality in remote collaboration, Mixed Reality (MR) can blend real whiteboards across distributed spaces. Going beyond reality, MR can further enable interactions like panning and zooming in a virtually reconfigurable infinite whiteboard. However, this reconfigurability conflicts with the sense of physicality. To address this tension, we introduce Blended Whiteboard, a remote collaborative MR system enabling reconfigurable surface blending across distributed physical whiteboards. Blended Whiteboard supports a unique collaboration style, where users can sketch on their local whiteboards but also reconfigure the blended space to facilitate transitions between loosely and tightly coupled work. We describe design principles inspired by proxemics; supporting users in changing between facing each other and being side-by-side, and switching between navigating the whiteboard synchronously and independently. Our work shows exciting benefits and challenges of combining physicality and reconfigurability in the design of distributed MR whiteboards.

*Both authors contributed equally to this research.

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CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; **Collaborative and social computing systems and tools**; **Empirical studies in collaborative and social computing**.

KEYWORDS

mixed reality, avatars, remote collaboration, proxemics, f-formations, 3C collaboration model

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1 INTRODUCTION

Whiteboards are indispensable tools for collaboration. However, conventional whiteboards demand that team members share the same physical space. As remote work becomes more prevalent, modern workplaces have embraced virtual whiteboards, such as Miro [35] or Mural [53], extending whiteboard activities to geographically dispersed teams. Virtual whiteboards provide new types of reconfigurations of users and content, such as panning, zooming, and pointing to the whiteboard content in an infinite canvas. Yet, virtual whiteboards lack essential ingredients of physicality: the immediacy of pen-to-surface interaction, the rapid attention switching between person and task, and the bodily turn-taking that is negotiated in front of a physical surface.

In this paper, we envision how Mixed Reality (MR) can be used to combine the *physicality* of the real whiteboard with the *reconfigurability* of the virtual whiteboard. To this end, we introduce Blended Whiteboard—an MR system for remote collaboration that combines physical surfaces and virtual avatars into a blended whiteboard workspace, which can be reconfigured to suit users' collaborative needs. Prior related work has either focused on supporting physicality through MR [15, 18, 63] or workspace reconfigurability through other display types [14, 17, 30, 62]. However, this work focuses on the tension that arises from using MR to combine the two.

Blended Whiteboard applies three design principles, which are derived from a theoretical lens on collaboration inspired by proxemics [16, 23] and the 3C model [3, 9]. The system enables Alice and Bob to meet remotely while appearing next to each other as embodied avatars, each in front of their real whiteboard. They can rely on natural non-verbal cues to communicate and take turns sketching on the whiteboard. But Alice and Bob are not tied to the physical constraints of real whiteboards. For instance, the *Dynamic F-formations* Principle enables them to switch from being next to each other to working through the whiteboard (Figure 1A). This way, they can now communicate by sketching and pointing to content simultaneously in the same canvas area without avatars being in each other's personal space. When working through the whiteboard, content is mirrored (akin to [21]) such that the orientation of content and pointing gestures remain meaningful.

After a close cooperation, Alice and Bob might decide to divide a task and work independently. To support these changes in collaboration styles, the system follows the *Dual-Mode Navigation* Principle, providing two modes of whiteboard navigation: *canvas* mode for tightly coupled work, and *viewport* mode for loosely coupled work.

Supporting individual navigation is important for effective whiteboard cooperation, but it also highlights a tension between physicality and reconfigurability. When Alice navigates her viewport through panning (Figure 1B) and zooming (Figure 1C), it also changes distance and scale between avatars. When using Blended Whiteboard for loosely coupled work, users may deliberately want to change distance and scale between avatars, but doing so can also compromise natural (physical) non-verbal cues. Thus, to regain the sense of physicality, the *Reversible Transitions* Principle allows Alice to return back to real-world scale and distance between avatars.

Our paper demonstrates and discusses this balancing act between physicality and reconfigurability. Through insights from proxemics theory, design principles development, and a user study, we highlight how different blended whiteboard configurations enable different collaboration styles, and discuss how Blended Whiteboard provides a spectrum between physical and reconfigurable use to suit different whiteboard tasks. As such, this work contributes:

- Three design principles for MR whiteboards—*Dynamic F-formations*, *Dual-Mode Navigation*, and *Reversible Transitions*.
- A novel remote collaboration system, Blended Whiteboard, that demonstrates how the three principles can combine physicality and reconfigurability.
- A theoretical lens applied to empirical insights of a user study for understanding the tensions in supporting remote whiteboard collaboration through MR.

2 RELATED WORK

Prior work on distributed whiteboards and workspaces either focuses on increasing physicality with MR, or providing reconfigurable workspaces with VR and situated screens (Figure 2).

2.1 Physical interactive whiteboards enable high physicality but low reconfigurability

Beyond physical and virtual whiteboards, research has proposed early prototypes of interactive whiteboard systems designed to be situated in office environments on displays or projectors. These augment physical whiteboards with stylus-based interactions, such as mixing multi-media with pen strokes [4], inferring objects from sketches [40], and supporting multi-device interactions [46].

Some research prototypes have focused on providing strong remote co-presence during collaborative sketching on a whiteboard surface [21, 57]. *VideoWhiteboard* [57] is a whiteboard-sized drawing space for remote collaborators. Each user sees drawings and a shadow of the gestures of collaborators at the remote site, captured using cameras and displayed by projecting users' hands and

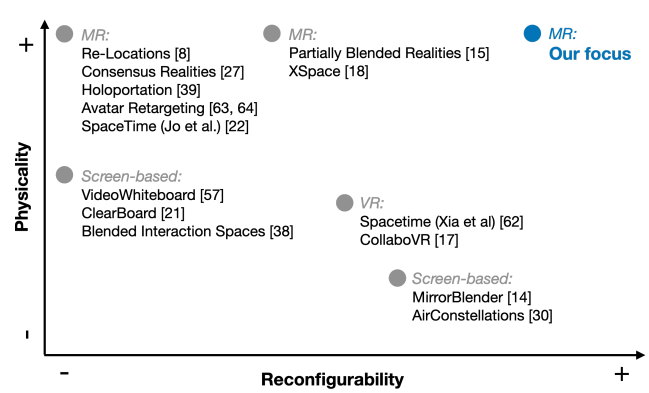

Figure 2: Related work mapped along key dimensions of physicality and reconfigurability.

arms on the drawing surface. *ClearBoard* [21] offers a remote whiteboard experience where users sit face-to-face while drawing on a transparent glass-like surface that appears to be between them. They see the remote user as a live video that is mirrored such that their writing appears with the correct orientation for the other participant, despite breaking the physical metaphor of a transparent glass surface. In Buxton's terms [1], these systems provide a unique reference space, which integrates the person and task space in a way that users can view task-related whiteboard content while simultaneously reading off bodily and deictic cues from their remote collaborators behind the content.

However, situated displays as whiteboard solutions do not meet the needs of today's "anywhere work"—they require static setups in dedicated environments and they blend remote sites in a *preconfigured* way, allowing little flexibility for remote users to reconfigure the arrangement of their blended collaborative space.

2.2 Dynamically reconfigurable virtual spaces lack physicality

Research has explored new kinds of interfaces to create reconfigurable spaces for dynamic collaboration styles, ranging from shape-changing physical surfaces [12, 13, 54, 55], through dynamic video-conferencing [14, 30, 35, 52] to collaborative VR spaces that play with notions of space and time [17, 32, 49, 62]. Falling between these two ends is the concept of *AirConstellations* [30], which offers a shape-changing multi-device workspace, providing multiple spatial mobile-device configurations on a semifixed movable armature. The system demonstrates new forms of spatially configurable videoconferencing that afford proximity-based interactions between remote users.

However, solutions designed for remote collaboration tend to compromise the physical nature of collaboration. For instance, the open-source software *Gravity Sketch* [49] provides a VR space to sketch collaboratively in mid-air. To provide a flexible reconfigurable space, such solutions tend to compromise the physicality, e.g., the sense of sketching on a real surface, or the avatars resemblance to human bodies to avoid invading each others' personal space. Moverover, the CollaboVR system [17], which is a highly related system to our concept, provides a remote collaborative VR environment that offers flexible configurations of people and surfaces. Users can choose both the location of the remote participant and the location of the surface.

In line with CollaboVR [17], we aim to balance the physicality of in-person interaction with new kinds of virtual capabilities to reconfigure interpersonal space between avatars of remote users. However, we focus on the tension that arises from using MR, i.e., VR is not constrained to the physical space while MR is, specifically, to enable reconfigurations. Moreover, we complement the results of the CollaboVR study with application-specific challenges related to supporting dynamic whiteboard collaboration.

2.3 Mixed Reality creates a trade-off between physicality and reconfigurability

With Mixed Reality (MR), new blending possibilities arise, allowing distributed users to physically move around in their local space while embodied together in a shared virtual space [39, 41]. Most MR systems tend to require pre-configuration of the physical spaces to create a blended space. But with the shift to remote work, researchers have started to explore systems that align distributed dissimilar workspaces, i.e., spaces that are not physically designed to be blended. Solutions include functional space discretisation [64], warped gestures [25, 50, 63], adaptive avatar movements [2, 22, 60], and optimal partial alignment [8, 27].

These systems enable new flexibility to blend remote spaces, but they are not reconfigurable. More recently, researchers have proposed partially blended spaces that can be dynamically defined [15, 18]. The concept of Partially Blended Realities (PBR) by Grønbæk et al. [15] offers a solution, focusing on mapping relevant surfaces for tasks rather than aligning the whole space. The goal is then shifting to allow users to realign their spaces as they transition to different spatial relations to each other and their physical surfaces. Grønbæk et al. found that when realigning surfaces, the transitions between configurations require users to readjust their mental model of the shared space in relation to their local physical space. The implication here is that once we enable reconfigurability, it starts to conflict with the sense of physicality.

In our work, we build on the PBR concept and results. We extend their work by focusing on whiteboard application-specific challenges to enabling reconfigurable distributed MR collaboration. While PBR suggests reconfigurations to *align surfaces* across dissimilar spaces, our paper focuses on enabling users to *dynamically reconfigure surface relations* to switch between independent and joint whiteboard tasks.

2.4 Proxemics motivates the need to combine physicality and reconfigurability

Theories of proxemics and f-formations provide a useful lens for understanding the need to blend spaces for distributed collaboration [15, 26, 38, 51, 61]. Proxemics, pioneered by Hall [16], studies how the spatial configuration and opportunities of the physical environment shape interpersonal distance and orientation. Along these lines, Kendon introduced the f-formation system (shorthand for facing formations between people) [23, 24], offering a visual vocabulary for capturing the top-down physical arrangement of people conducting interaction in groups, such as *side-by-side* or *face-to-face* formations. In Human-Computer Interaction research, such vocabulary helps to describe the physical spatial configurations of people in relation to interactive surfaces [26, 31, 42], and studies show that different surface configurations afford different collaboration styles [12, 47, 48]. Research shows that a co-located group's particular choice of facing formation shapes their collaborative coupling styles [56], often revealing a pattern where close physical interpersonal distance affords *working tightly together*, whereas further interpersonal spacing provides better means for *loosely coupled* collaboration [45, 56]. In remote settings, however, these dynamics around shared surfaces have obviously shown to have a less physical bodily nature [59], and in hybrid settings, they create communication asymmetries [36, 37]. But evidence from studies of social VR spaces suggest that (proxemic) spatial relations remain influential in remote settings [17, 33, 61]. The dynamics afforded by MR settings, however, have been less investigated.

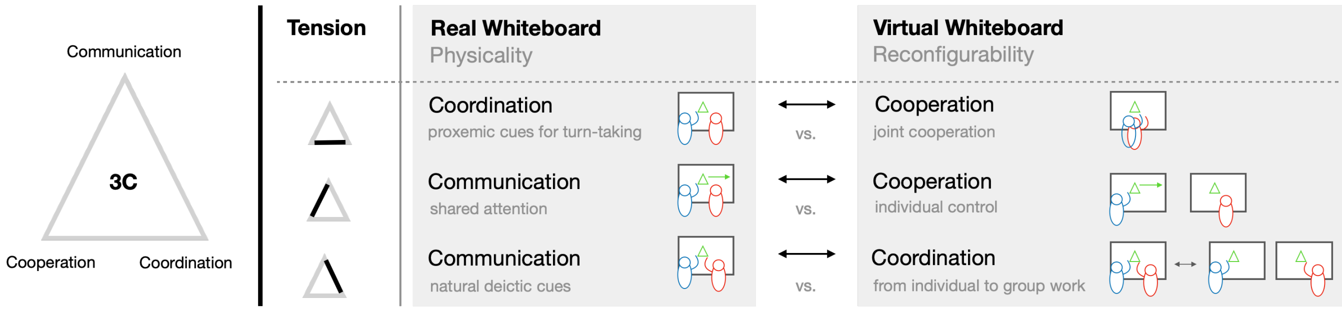

Figure 3: Tension between physicality and reconfigurability through the lens of the 3C model [3, 9]. Real whiteboards support *physicality*: bodily coordination for turn-taking through proxemic cues, effective management of shared attention on the same surface area, and natural deictic communication cues for pointing. Virtual whiteboards support *reconfigurability*: joint cooperation without bodies in the way of each other, individual control for cooperating independently, and effective means for coordination between individual and group work. These respective benefits of real and virtual are not exhaustive, but when in juxtaposition to each other, they exemplify tensions in designing MR whiteboards.

A proxemics-inspired concept more closely related to our paper is O'Hara et al.'s *Blended Interaction Spaces* [38], arguing that spatial geometries (related to people, objects and spaces) can be aligned such that distributed teams and their workspaces become *blended* [38]. We build on this concept but extend it to consider the reconfigurability of blended spaces. This idea is inspired by proxemics-informed literature on computer-supported collaborative work (CSCW), which shows that when observing physically co-located work over time, collaborators often switch between different collaboration styles, leading to transitions between f-formations [11, 26, 29, 58]. This motivates the need for collaborative interfaces to support users in spatially reconfiguring their work environment for the task at hand, which has not previously been considered for supporting remote MR collaboration.

3 MIXED REALITY WHITEBOARDS: PHYSICALITY VS. RECONFIGURABILITY

We envision an MR whiteboard that enables remote users to work on their real whiteboards while also flexibly reconfiguring their shared workspace for the task at hand. To articulate this design problem, we describe properties of *physicality* and *reconfigurability* for whiteboard collaboration and build upon the 3C collaboration model [3, 9] to unpack the tension between them. This serves as the theoretical foundation for the design of Blended Whiteboard.

3.1 Physicality and real whiteboards

Physicality refers to features of the shared environment with spatial geometries that support innate human abilities to use effective non-verbal communication, e.g., bodily cues for turn-taking at the whiteboard, managing shared attention through gaze and gestures, and deictic referencing for more effective talk. When surfaces and spaces are blended, physicality is achieved by enabling people's bodies to engage with each other and the shared environment.

With a real whiteboard, the physical interaction of a pen touching a flat surface affords direct and spontaneous sketching, handwriting and diagramming, as well as annotations on top of each other's scribbles. The spontaneity of bringing the pen to the surface makes the physicality of whiteboards convenient for collaborative activities that require rapid turn-taking, such as brainstorming, presenting and critiquing ideas, or organising information at the early stages of sense-making. In recent years, interactive whiteboard displays, such as the Surface Hub [34], have gained traction. These displays are situated in a physical setting, providing much of the physicality of the real whiteboard. They typically feature styluses for physical sketching but also support multi-touch gestures, such as zooming and panning whiteboard content.

3.2 Reconfigurability and virtual whiteboards

Reconfigurability refers to users' ability to change the spatial relations between collaborators and shared objects on demand, e.g., re-organizing space for joint work or coordinating transitions between individual and group activities. Examples of spatially reconfigurable workspaces include screen-based interfaces for remote collaboration [14, 30] and physically shape-changing interfaces for co-located collaboration [13, 54, 55].

The recent shift to remote work has paved the way for new reconfigurable workspaces for whiteboard interaction, with accelerated popularity of distributed virtual whiteboard solutions such as Miro [35], Mural [53], or Zoom Whiteboard [65]. These solutions provide infinite canvases where content is virtually zoomable and pannable. Due to the absence of physical bodies in front of the shared canvas, these virtual interactions afford a different collaboration style where users can dynamically reconfigure the 2D spatial relation between content and users, typically using cursors for deictic communication and viewport indicators for awareness of other users.

3.3 Understanding the tension

Physical and virtual whiteboards have complementary affordances, catering to different needs in terms of physicality, interactivity, and collaboration. We aim to combine the best of both worlds, but this creates a tension (Figure 3). To better understand this tension, we leverage the 3C model [3, 9], which structures collaboration as three activities: *communication*, where users negotiate and make

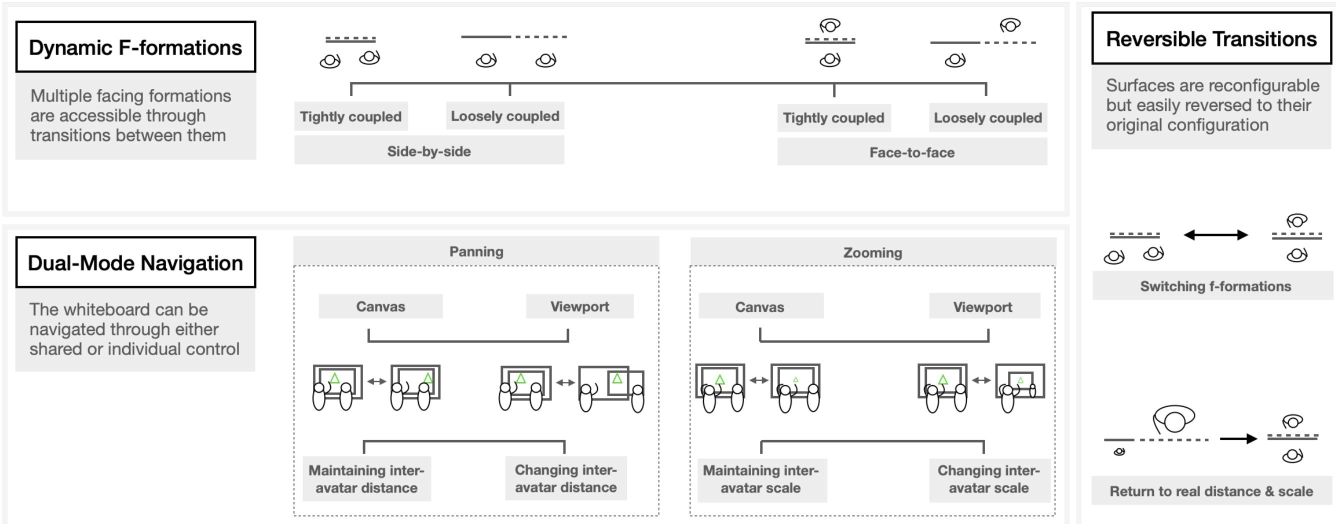

Figure 4: Overview of Blended Whiteboard design principles.

decisions; *coordination*, where users manage conflicts and organise activities; and *cooperation*, where users manipulate objects and execute tasks. These activities are interdependent, where communication generates commitments managed by coordination, which arranges activities for cooperation, which in turn, requires communication for its successful execution. We argue that physical and virtual whiteboards excel at different aspects of these activities, creating the following conflicts (Figure 3, rows):

Coordination vs. Cooperation. Alice and Bob want the ability to stand next to each other in front of a real whiteboard and use their bodies to non-verbally coordinate the turn-taking of sketching on the whiteboard. But they might also need to cooperate on the same content without being in the way of each other's bodies. The physical position and orientation of their bodies facilitate coordination but hinder cooperation. Virtual whiteboards allow an arbitrary number of users to cooperate on the same object, but they cannot leverage proxemics to easily coordinate this activity.

Communication vs. Cooperation. When they work closely together and directly communicate, Alice may want to navigate the infinite canvas such that Bob can see exactly what she sees; this requires shared attention through the same viewport, akin to how interaction on touch-sensitive smartboards works. But when they cooperate (i.e., working together but independently), Alice needs independent controls to navigate without disrupting Bob's actions. So to facilitate communication, one user must control what the other sees, but to facilitate cooperation, each user must have control over their own viewport.

Communication vs. Coordination. To communicate effectively with Bob, Alice must be able to use deictic referencing while discussing whiteboard content. But Alice and Bob also want the flexibility to coordinate shifts in their work between independent and joint activities. Pointing at the content on a physical whiteboard is intuitive, but coordinating between individual and group work is difficult. Virtual whiteboards allow users to easily move content around the canvas (e.g. by copying content from a personal workspace to a shared board). However, the lack of embodiment in virtual whiteboards hinders non-verbal communication.

In sum, though both the physicality of real whiteboards and the reconfigurability of virtual whiteboards are desirable, bringing them together creates a tension in how they support communication, coordination, and cooperation.

3.4 Design principles

Through the lens of proxemics theory and the 3C collaboration model, we derive three core design principles for MR collaborative whiteboards (Figure 4).

- *Dynamic F-formations*: multiple facing formations should be accessible through transitions between them;
- *Dual-Mode Navigation*: the whiteboard should be navigated through either shared or individual control; and
- *Reversible Transitions*: surfaces should be reconfigurable but easily reversible to previous configurations.

4 BLENDED WHITEBOARD: SYSTEM DESIGN

The Blended Whiteboard is an MR proof-of-concept system that applies the three design principles to reconcile the conflicting implications of physicality and reconfigurability. In the following, we describe its design and implementation.

4.1 Overview

The Blended Whiteboard system is an MR collaborative whiteboard that allows two remote users to work in front of a local physical whiteboard. Each physical whiteboard can have a different size (Figure 5A). Remote users are represented by embodied avatars positioned relative to each user's local physical whiteboard. The system supports two facing formations: side-by-side (Figure 5B), and face-to-face (Figure 5C).

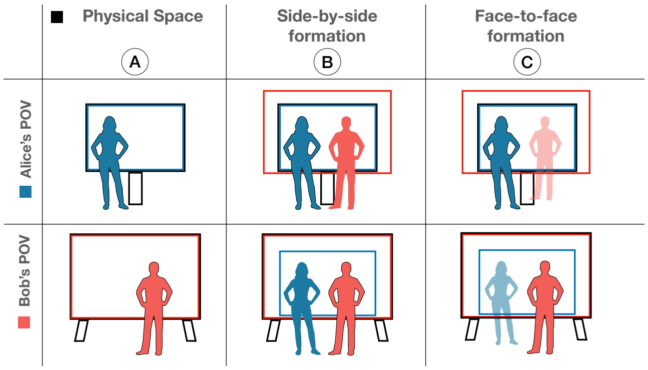

Figure 5: Physicality and f-formations in blended space: When the system overlaps users' local whiteboards, it creates a shared viewport into the same virtual whiteboard canvas.

4.2 Facing formation modes

Blended Whiteboard implements the *Dynamic F-formations Principle* (Figure 4). First, the virtual sensation of a physical facing formation is created by aligning the surfaces (Figure 5). Avatars can be arranged in relation to the blended whiteboard surface to support a range of collaboration styles with two main kinds of f-formations, i.e. side-by-side (Figure 5B) and face-to-face (Figure 5C) as well as transitions between them.

4.2.1 Side-by-side. The side-by-side formation (Figure 5B) enables a more traditional collaboration style, resembling how co-located people naturally stand next to each other in front of a whiteboard. This f-formation enables users to leverage non-verbal cues for turn-taking to sketch and coordinate their work on the whiteboard surface.

4.2.2 Face-to-face. The face-to-face formation (Figure 5C) allows collaborators to face each other with a shared canvas between them. An in-person analogue to this formation would be a transparent whiteboard with collaborators on both sides. Similar to ClearBoard [21], Blended Whiteboard flips the rendering of the collaborator's avatar and whiteboard content so that both users can still read handwritten text in the correct orientation and perceive pointing gestures with spatial consistency. Because this formation involves a physical barrier, it enables joint cooperation, even while sketching in the same surface area, because collaborators' avatars are not in the way of each other.

4.2.3 Mirroring: switching between facing formations. The mirroring transition enables collaborators to change between side-by-side and face-to-face formations by pressing a button on the hand controllers. When the mirroring is triggered, it initiates an animation where the avatar is floating through the whiteboard while rotating to the right orientation on the other side (Figure 6). This illusion helps the user perceive the transition to build a mental model of the transformation, as opposed to a sudden teleportation, for example.

4.3 Whiteboard navigation modes

Blended Whiteboard implements the *Dual-Mode Navigation Principle* (Figure 4). The whiteboard can be navigated through modes of

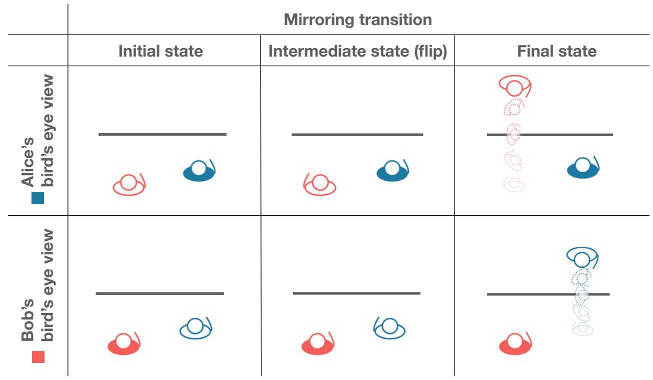

Figure 6: Mirroring transition from side-by-side to face-to-face formation. In each row, solid color bodies refer to the real user, whereas transparent bodies refer to the partner's avatar. Whether Alice or Bob triggers the transition, they perceive it as their partner's avatar floating through the whiteboard. The users perceive the transition as an animation without interruptions, however, to explain it step by step, we divided the animation into three states, one per column (initial, intermediate, and final). The *initial state* shows a depiction of reality, with both Alice and Bob right-handed (i.e., the dominant hand is extended for interaction). In the *intermediate state*, the avatars of the remote partner are instantly flipped on one axis into a mirrored representation. To reach the *final state*, both users perceive their partner's avatar rotating with an animation through the whiteboard.

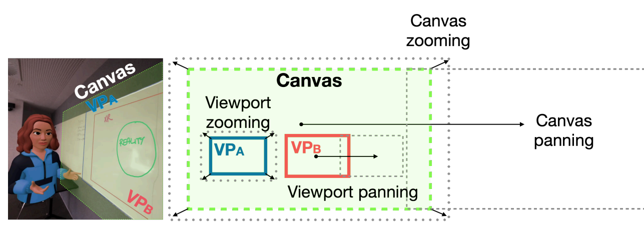

Figure 7: Blended Whiteboard navigation: users can pan and zoom the content on a virtually infinite whiteboard canvas. Alice can choose between navigating the canvas (which is shared with Bob) or her individual viewport (VP_A). The *canvas* refers to the infinite virtual surface, whereas the *viewports* are the local physical whiteboard surfaces.

either shared or individual control. The two modes are designed to support working either jointly or independently. To provide both modes simultaneously, we model Blended Whiteboard after the familiar virtual whiteboards, which are composed of one *canvas* and multiple *viewports* (Figure 7). The *canvas* refers to the shared infinite virtual whiteboard, whereas *viewports* refer to the local physical whiteboard surfaces through which each user can view and interact with the canvas. Users can switch between two modes of navigation; when Alice navigates, her action either manipulates the shared canvas (Figure 8), i.e. affecting both her and Bob's view, or merely her own individual viewport (Figure 9 and Figure 10).

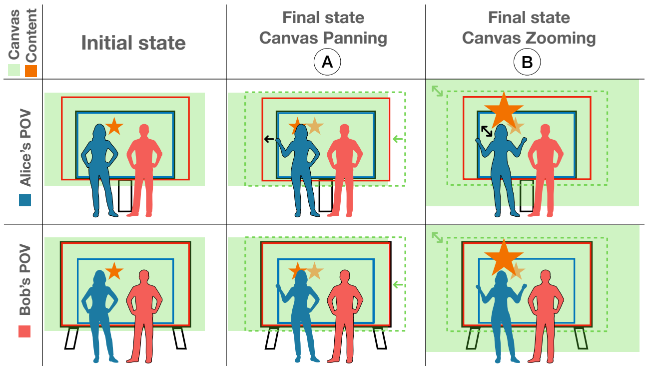

Figure 8: Canvas panning and zooming. In the initial state Alice and Bob see a similar portion of the shared canvas (in green) through their individual viewports (in blue and red, respectively). A: Alice pans the canvas to the left. B: Alice zooms in. Bob and Alice see the same final state through their viewports in both cases.

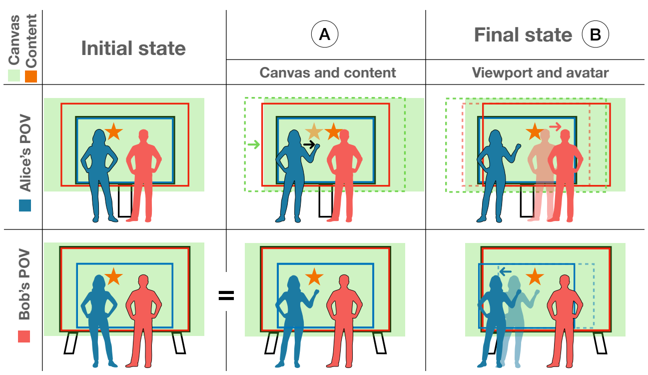

Figure 9: Viewport panning. In the initial state, Alice and Bob see a similar portion of the shared canvas (in green) through their individual viewports (in blue and red, respectively). A (Alice's POV): she pans her own viewport to the right (black arrow). B (Alice's POV): For her, it appears that Bob moved with the canvas to the right. B (Bob's POV): While Bob perceives this as if Alice moved to the left.

The mode switch is defined by proximity to the local surface. If she touches the surface, she navigates the *canvas*—if she navigates from a distance, she only manipulates her *viewport* (Figure 11C).

Our terminology for whiteboard reconfiguration focuses on navigation. However, as described in 3, there can be multiple reasons and motivations to reconfigure the whiteboard workspace. Returning to the 3C model, the three types of activities outline the different kinds of motivations; they can be either *communication-related* (e.g., changing distances in the facing formation for different deictic abilities), *cooperation-related* (e.g., whiteboard task-related actions such as sketching, sticky noting, or navigating content), or *coordination-related* (e.g., changing spacing and orientation to partner and content to change between parallel and joint work). Next, we will examine some examples of these.

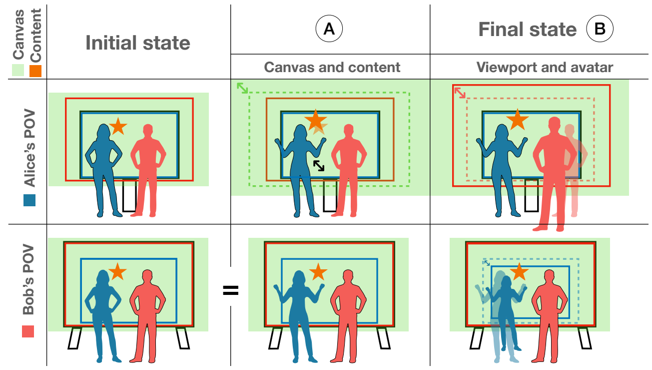

Figure 10: Viewport zooming. In the initial state, Alice and Bob see a similar portion of the shared canvas (in green) through their individual viewports (in blue and red, respectively). A (Alice's POV): she zooms into her own viewport. B (Alice's POV): For her, both the canvas and Bob's avatar appear larger. B (Bob's POV): while Bob perceives this as if Alice shrunk, while the canvas remained at the same size.

4.3.1 *Panning and avatar repositioning.*

When panning, users can choose between panning the canvas for everyone or merely their own viewport.

Canvas panning modifies the whiteboard canvas while keeping the avatar space untouched for both users. This is a symmetric transformation, which benefits communication as it can maintain shared attention on the same view of the canvas during panning. Figure 8 shows this interaction being performed by Alice (in blue). Alice can displace the canvas for both her and Bob to shift their shared attention to a desired location. However, it is important for users to coordinate this action to avoid disrupting each other, as this interaction technique shifts the canvas for both users at the same time.

Viewport panning, in contrast, displaces Bob's entire virtual space (avatar and viewport surface), superimposed on Alice's physical reality (Figure 9). This is an asymmetric transformation, which has coordination benefits, as it allows Alice to work in parallel with Bob without disrupting his current work. But viewport panning can be used for several purposes. One is to transform the avatar relation. Another is to merely navigate the content independently. First, this is useful when Alice and Bob are working individually with distributed attention, as Alice's panning interaction is not obtrusive to Bob's perception of the shared space. Second, viewport panning can change the interpersonal distance between avatars (e.g., to coordinate a switch to parallel work) rather than merely panning to view another part of the canvas (as illustrated in Figure 1).

4.3.2 *Zooming and avatar rescaling.*

Blended Whiteboard supports zooming to scale the content on the whiteboard, allowing users to switch between an overview and detail (Figure 10). On a physical whiteboard, we do this naturally by moving between different distances to the surface. However, it remains constrained to the limited size of the whiteboard. With virtual whiteboards, users have infinite canvases that are zoomable and pannable. This affords the

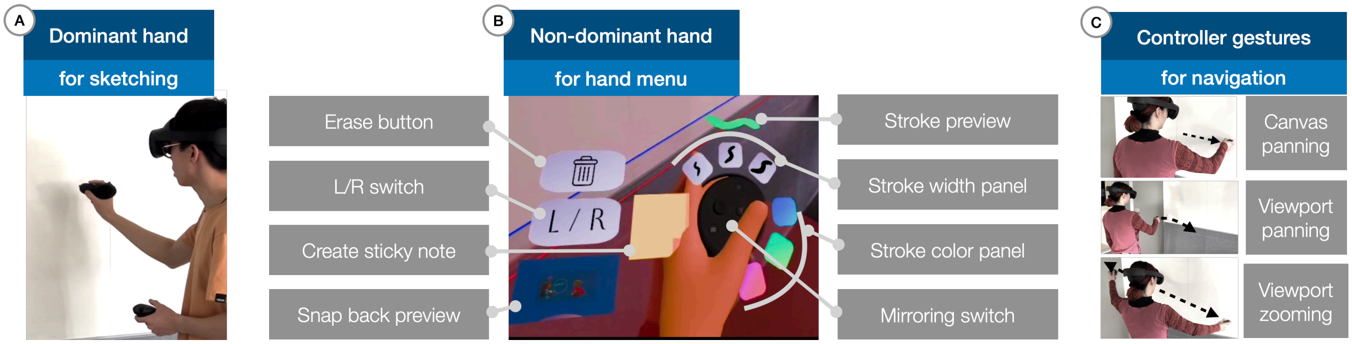

Figure 11: Blended Whiteboard interaction. *A:* Physical sketching with stylus. *B:* Hand menu. On their non-dominant hand, they have a hand menu with tools for reconfigurability. Tools are activated when the stylus on the dominant hand collides with the tool button. *C:* Controller gestures. *Canvas panning:* the user pans while pressing down the grab button and touching the surface. *Viewport panning:* the user pans mid-air while pressing down the grab button. *Viewport zooming:* the user stretches or shrinks the distance between both hands while pressing the grab buttons in both controllers simultaneously.

ability to create larger information spaces through sketching or diagramming. But with larger information spaces comes an increased need for coordination and managing distributed attention. Thus, to support zoom navigation, Blended Whiteboard also enables both canvas and viewport zooming.

Again, when Alice and Bob work with shared attention on the canvas, they can take turns zooming in. But when they switch to parallel work, they must zoom in a way that does not affect the partner. Here, we encounter a consequence of the Blended Whiteboard design: Blended Whiteboard preserves the physical scale between a user (avatar) and their local whiteboard (viewport)—this is a deliberate choice to preserve the sense of a physical reference frame for each user. However, as a consequence, avatar relations are then scaled during viewport zooming (Figure 10B). While this reduces the communication-related qualities of physicality, it helps coordination by indicating that their partner is working at a different level of detail on the shared canvas.

4.4 Snap back to reality

Finally, Blended Whiteboard implements the *Reversible Transitions Principle* (Figure 4). Reconfigurations of the system can lead to scaled and repositioned avatar relations. Similar to virtual whiteboards, the lack of a shared reference frame can make it difficult to monitor the partner's attention. Thus, to resolve spatial inconsistencies, users may benefit from the ability to reset scale and distance to restore a sense of physicality. To address this need, Blended Whiteboard provides a shortcut to join the partner's viewport frame.

Imagine Alice and Bob have zoomed in on different areas, and Alice has zoomed into a detail while Bob remained at the overview (Figure 1C). At this point, Alice may invite Bob over to see the detailed sketch she is working on. At this point, Bob can turn his non-dominant arm wrist to see his hand menu (Figure 11B) where he is presented with live preview of the partner's POV. This preview can be tapped to trigger an animation that transforms Bob's viewport into the same position and scale as Alice's viewport. By the end of the transition, Alice and Bob will have returned to natural eye-level communication, re-establishing a sense of physicality. We will refer to this interaction as "Snap Back to Reality"—as a demonstration of the system's capability to reverse transitions that destabilise the physical properties of the blended space.

4.5 Implementation

The Blended Whiteboard proof-of-concept was developed in Unity (v2021.3.17f1) using Oculus Integration (v50.0), the Meta Avatars SDK (v18.0), and the Photon Engine PUN2 (v2.41) as the library for multi-user networking. The system was deployed in two Meta Oculus Pro, using their controllers with the stylus tips add-on.

4.5.1 User inputs. Blended Whiteboard supports interactions on a real whiteboard surface via a stylus controller (Figure 11A). The system features a hand menu to trigger actions and a set of controller gestures for whiteboard panning and zooming (Figure 11).

4.5.2 Setup. When an interactive session starts, the user must first define their local whiteboard surface to use for remote collaboration, similar to Grønbæk et al. [15]. The local user defines the surface by selecting two opposite corners of their physical whiteboard. Once defined, the user has created their viewport into the infinite canvas (Figure 5A). Then, collaborators tap to join in a shared session. Once joined, the whiteboard surfaces are aligned with avatars spawned in the side-by-side formation. Each user has a viewport represented by a distinct colour, i.e., red and blue (Figure 5B).

5 USER STUDY

To gain insights into the opportunities and challenges of dynamic MR whiteboard configurations, we studied pairs of remote users collaborating via Blended Whiteboard in a lab setting. We were interested in questions related to the Blended Whiteboard design principles related to facing formations and whiteboard navigation. To design an experiment that compares different configurations of facing formations and navigation modes, we derive four possible conditions for comparison in a 2-by-2 table Blended Whiteboard configurations (Table 1).

RQ 1. What are the pros and cons of side-by-side vs. face-to-face formations? We study this question by comparing the reported user experience across conditions in the columns of Table 1.

RQ 2. What are the pros and cons of canvas vs. viewport navigation? We study this question by similarly comparing rows of Table 1.

RQ 3. During collaborative whiteboard tasks, how do users resolve tensions between physicality and reconfigurability using the Blended Whiteboard system? We observe and interview pairs about using the full system, with a focus on understanding whether users rely on physical transitions (i.e., bodily movement dynamics of avatars), virtual transitions (i.e., reconfiguring the blended space), or both, during collaborative whiteboarding.

5.1 Study design and procedure

Participants were placed in two adjacent office rooms with similar layout and placement of a physical whiteboard, with each participant wearing an MR headset featuring the Blended Whiteboard system and hearing their partner through a separate audio connection via a speaker placed right above each local whiteboard. An experimenter was seated in each room outside the participant's view of the whiteboard area to observe and help managing the headset and progressing in the study. We recruited 24 participants (12 pairs), with 13 men and 11 women (gender was self-reported), aged between 23 and 26. Participants filled in a pre-questionnaire with demographic information, including a rating of how well they knew their partner. Participants declared familiarity with their partners $\bar{x} = 3.38$ ($\sigma = 1.42$), on a range between 1 (not at all) to 5 (very much). It was an intentional effort to recruit pairs who knew each other in advance, so as to ease the process for partners to agree on a common goal for the whiteboard task in the study's second part. All sessions were recorded both via room cameras in each room and POV recordings from the headsets. Observational notes were taken by researchers in each room.

The study was divided into two parts, with the first part focused on comparing mode configurations (RQ 1 and 2) and the second part focused on transitions using the full system (RQ 3).

5.2 RQ 1 and 2: Comparing mode combinations

The first part (40-50 mins) compares configurations in terms of their pros and cons for solving affinity diagramming tasks.

5.2.1 Study design and analysis. We designed a 2-by-2 comparison of the possible configurations (f-formation × navigation mode, see Table 1). For fair comparison and to keep it simple, the system was configured to only enable grabbing and moving of virtual sticky notes on the whiteboard, and one mode of panning when the user performs grabbing areas outside of sticky notes. All grab and move actions were performed by holding a button on the handheld controller.

- **Side-by-Side Canvas:** Partners' avatars are side-by-side, and panning is fixed to canvas mode irrespective of the user controllers' distance to the surface.
- **Side-by-Side Viewport:** Avatars: side-by-side, panning: viewport.
- **Face-to-Face Canvas:** Avatars: face-to-face, panning: canvas.
- **Face-to-Face Viewport:** Avatars: face-to-face, panning: viewport.

To compare the collaborative experience across conditions, pairs repeated the same task in each condition with varying content. The order of conditions was counterbalanced across pairs. The task was a 5-minute affinity diagramming exercise. Pairs were asked to sort a set of prelabeled sticky notes into predefined categories (see Figure 12). The affinity diagramming task was simple and allowed pairs to choose their collaboration strategy; whether to distribute the labour or work in synchrony, discussing every label's category.

Before each task, participants spent 1-3 minutes getting familiar with the task (first training) and the condition.

Between each condition in Part 1, participants were asked to complete questionnaires. We included the following statements to get insights on usability, collaboration, and personal space, rated

Whiteboard panning	F-formations: Side-by-side	F-formations: Face-to-face
Canvas	***SbSCanvas*** - Avatars next to each other - A+B: only content moves	***F2FCanvas*** - Avatars in front of each other - A+B: only content moves
Viewport	***SbSViewport*** - Avatars next to each other - A: B's avatar + content move - B: A's avatar moves	***F2FViewport*** - Avatars in front of each other - A: B's avatar + content move - B: A's avatar moves

Table 1: We study a 2-by-2 comparison of blended space configurations. Each mode configuration is a condition; with differences in what is perceived when user *A* pans content while *B* views passively.

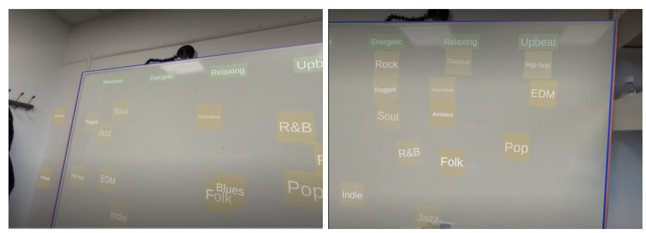

Figure 12: Task for 2-by-2 comparison: affinity diagramming. At the top are four category labels (green). Below, 15 sticky notes (yellow) are randomly spawned, with some outside the physical board to encourage the use of panning. Left: Before the task, sticky notes are unsorted. Right: Participants complete the task by grabbing and arranging sticky notes into each category.

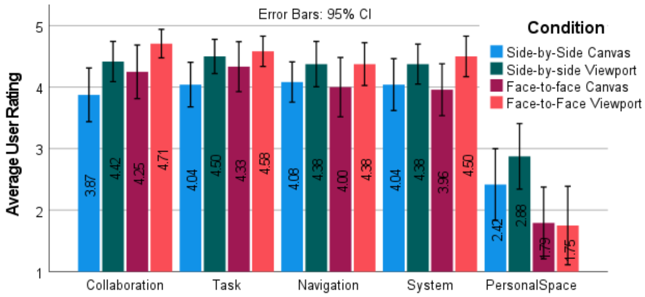

Figure 13: Study results on the ratings for each condition, on usability of four system parts and the effect of personal space intrusion.

on a Likert scale from 1 (strongly disagree) to 5 (strongly agree): (1) It was easy to collaborate with my partner, (2) It was easy to accomplish the task together, (3) It was easy to navigate the canvas, (4) The system supported the task well, (5) I felt my personal space was intruded upon (the data is visualized in Figure 13). Two open-ended questions asked participants to describe what they liked and disliked about the configuration. During analysis, the received open-ended questionnaire responses served as the primary data, processed by three researchers in three sessions to distill pros and cons of the mode combinations. Similar statements were grouped and counted to synthesize general participant responses, and these were complemented with the questionnaire ratings and relevant comments from the follow-up interviews.

5.2.2 Results. We synthesize user feedback in each condition into pros and cons regarding the experience of using different mode combinations to solve affinity diagramming tasks together.

To complement these qualitative results, we provide a chart with the average ratings of the questionnaire statements (Figure 13). We analysed the data with a Friedman test and Bonferroni-corrected Conover post-hoc comparisons. The statistics suggest the following significant effects. First, for the collaboration statement ($\chi^2(3)$ = 12.8, p = 0.005), users perceived *Side-by-Side Canvas* to be easier for collaborating with the partner than *Face-to-Face Viewport* (p = .004 ($\chi^2(3)$ = 12.8, p = .005)). Second, the avatar interaction with *Side-by-Side Viewport* was perceived to be significantly more intrusive to the users' personal space than with *Face-to-Face Canvas* and *Face-to-Face Viewport* (both p < .001 ($\chi^2(3)$ = 24.4, p < 0.001)). Next, we will elaborate on these issues based on the users' feedback.

Side-by-side vs. face-to-face formation. Four participants appreciated the close cooperation and easy communication that the side-by-side conditions offered. Participant 1a commented, "*It felt like moving real sticky notes*". However, six participants reported issues like avatar collisions and occasional disruptions. Participants 1a and 1b stated, "*Sometimes my partner clipped into my view*". Sticky note placement posed challenges, as evident through comments on the partner's avatar obstructing views. Both participants 2a and 2b noted occlusion to be an issue, e.g., "*Sometimes my partner was covering my frame, so I couldn't see properly*" (2a).

In the face-to-face conditions, six participants highlighted the immersive experience of feeling like they were collaborating in the same space. Participant 3a said, "*I felt very immersed in a shared space with my partner, as if we were on two sides of a glass window.*" The convenience of not having to turn their heads for interactions and the useful mirrored view for better understanding their partner's actions were seen as significant advantages by all participants.

Based on follow-up discussions in focus groups, however, the general impression is that most users favoured the face-to-face formation for this specific task.

Canvas vs. viewport panning. Under canvas mode conditions, seven participants appreciated the potential for efficient co-working and helping each other. Participant 4a mentioned, "*Other participants can help me move the board, and it could lower the effort for me to conduct my task*". The shared view was highlighted as beneficial, offering a common perspective and improving cooperation on the joint task. E.g., participant 8a stated, *"I knew what my partner was seeing because it was the same as me"*. Participants mostly valued the synchronized action when seeing their partners on the other side of the whiteboard. However, six participants reported challenges in the canvas setting. Conflicts often occurred when both participants wanted to move the board simultaneously, occasionally disrupting their workflow. For instance, sticky note placements were occasionally disrupted due to board movement. Participant 4a (and 4b similarly) described the issue, saying, "*Sometimes I was aiming at a sticky note to grab it and it 'flew away,' with me grabbing the air*". Similarly, the need to announce board movements was noted as an issue by participants 5a and 5b.

In viewport mode conditions, seven participants valued individual control of the canvas, allowing them to navigate and cooperate without disturbing their partner. Participant 1a stated, "*It was easy to navigate and work together to complete the task*" (Pariticipant 10a with a similar remark). In contrast, however, participant 7a stated "*Moving the canvas and a moving partner feel a bit unnatural*". When next to each other, it could cause intrusion to their personal space, as viewport panning may accidentally reposition avatars into each other's personal space.

5.3 RQ 3: Whiteboarding with the full system

In the second part (20-30 mins), the goal was to investigate interface challenges by observing Blended Whiteboard used as a full system for whiteboard interaction—including mode switches between configurations.

5.3.1 Study design and analysis. By the end of Part 1, participants were familiar with the available mode combinations. Thus, the training of Part 2 focused on showing the participants the zooming and hand menu, the mode switches (allowing users to freely transition between facing formations and navigation modes), and finally, the ability to return to eye level through a tap to join the partner's POV. To be able to observe more diverse use of the system, we let pairs come up with a whiteboard task themselves to complete in approx. 10 minutes. Due to technical issues with the sticky notes during mode switches, pairs were limited to sketching on the whiteboard directly during this task. The session started in side-by-side mode to begin with a natural whiteboard arrangement and observe how and whether they would choose to deviate from this when arranging themselves for the task at hand.

After the freeform task, we conducted a semi-structured focus-group interview with each pair. Interviews allowed participants to give retrospective accounts of their experiences from the entire study session. The focus-group format enabled the pair to revisit interesting incidents and discuss the similarities and differences between their individual experiences. Interviews focused on understanding pairs' unique experiences of performing their chosen task with the combination of facing formations, navigation modes, and transitions that they had used during the task. Interviews covered topics around immediate general impressions, added nuanced explanations of their experiences with the different mode configurations, and led to additional feature suggestions.

Recordings of interviews were analysed to derive themes related to the tensions between physicality and reconfigurability. To derive themes, two researchers used affinity coding of user comments from the interviews. Video recordings and notes from task sessions were revisited to identify examples and better understand the context of user comments. These examples were then used to complement the themes and specific user comments.

5.3.2 Results.

Physicality of side-by-side and face-to-face formations. Interestingly, although the second-part session started in side-by-side mode for all pairs, most pairs (8/12) chose to switch to the face-to-face formation, and only a third of the pairs (4/12) opted to stay in the side-by-side formation. Participants often found the side-by-side configuration initially natural but somewhat unsettling in practice due to the challenges of shifting their attention between the whiteboard content and the avatars. The limited field-of-view of the MR headsets caused more exaggerated head movements compared to the more subtle attention switching relying on the peripheral vision in physical space. Moreover, several interviewees provided examples highlighting issues with side-by-side configurations, such as the occurrence of uncanny sensations or visual occlusion. One participant even humorously mentioned how an additional hand would appear out of their chest when using side-by-side avatars. It was the general consensus across pairs that the face-to-face formation provided many benefits of physicality but with added benefits for affinity mapping and other tasks that require cooperation due to the simultaneous view of one's own interactions on the board and the awareness of the partner's actions. In the training phase, several participants initially reacted with surprise when discovering the left/right mirroring in the face-to-face configuration. They would often notice that their partner's avatar would do handwriting in reverse order, from right to left, to provide correct orientation for both participants. However, during the actual task, there were no further notable reactions to this effect.

The need for transitions between facing formations. While most participants preferred face-to-face, some participants did find side-by-side useful in specific situations, particularly during brainstorming sessions or when taking pauses during collaborative tasks. For instance, Pair 11 discussed their need to switch during their freeform task. This pair started by brainstorming ideas in synchrony and later cooperated on the whiteboard with simultaneous pen input.

While the partners generally agreed during their focus-group interview that face-to-face provided the most smooth collaborative configuration overall, an interesting discussion followed related to the need for transitioning between facing formations. Participant 11a added *"side-by-side was okay when we were collaborating more verbally than when working on the actual whiteboard"*. 11b followed with this reflection: *"When we brainstorm in real life, if there's a moment where we have to just pause and look at the board, we usually won't be looking at each other and just ... pausing"* (both laughing) *"... so it felt a bit more closer to what we actually do in real life when the person is just next to us [...]"*. *"Then afterwards when we re-ranked, [...] it was a bit more fast-paced"*. This is the moment where they actually switched in the task as well.

Some pairs relied on physicality, some relied on reconfigurability. The participants' choices of whiteboard task generally had a spatial nature, taking advantage of the ability to freely organize content on the whiteboard. Several pairs wrote lists (e.g., Figure 14, Pair 5 and 11), others created sketches together, e.g., a brain visualisation for a student project (see Figure 14, Pair 2), or diagrams (e.g., the planning of a holiday trip, like Pair 4). The different pairs' collaboration dynamics demonstrated a wide range of usage of the system. Pairs 2 and 5 offer examples of system usage at each end of the spectrum between physicality and reconfigurability. Pair 5 decided on writing a list of things for visitors to see in their local neighborhood. The pair remained in the side-by-side formation during this task, using it like a real whiteboard with no adjustments. Pair 2 decided to draw a brain together. They used the face-to-face formation during this task to cooperate on the same sketch. Moreover, extensive use of zooming was leveraged to switch between overview and detail while co-working on their collaborative sketch.

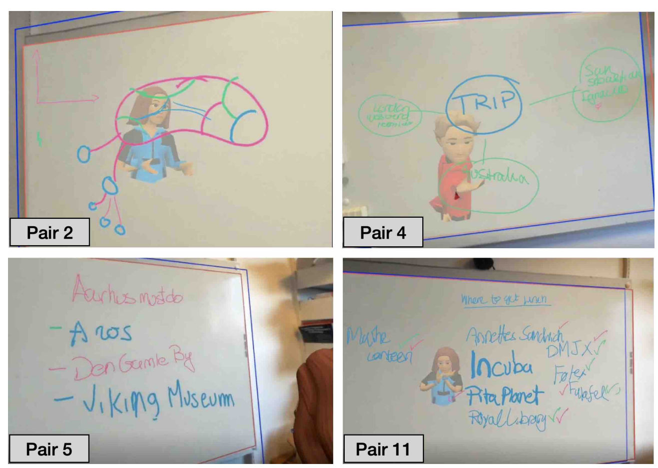

Figure 14: Selected outcomes of freeform whiteboard tasks.

Strong physicality, but reconfigurable when required. Throughout our observations and interviews, we noticed that participants often had strong positive reaction to Blended Whiteboard as a killer application for MR. Participants especially praised how the system anchored their remote collaboration in the real world, often making reference to how it improves presence compared to the current alternatives, such as Miro and Zoom Whiteboard. Several pairs would primarily use the system as if they were working on a physical whiteboard without reconfigurations, but when discovering a need, they would reconfigure, e.g., if content such as sticky notes were out of reach from support on the whiteboard surface, or virtually placed inside the local physical shelves next to the whiteboard.

In addition, we observed that participants sometimes forgot about the system's virtual flexibility due to the convincing illusion of a real whiteboard interaction. This led to instances where participants realized after the fact that they could have used certain reconfigurations, such as panning, for more ergonomic sketching postures. E.g., Participant 12a once could not reach whiteboard content, saying *"I am not tall enough"*. When asked during the interview, she elaborated *"I realized I could have just pulled it down. So I did that later on."* Similarly, 11b reported in the interviews that content was too low, and 11a commented that this can happen due to the physical surface interaction being so convincing that it tricks the brain into thinking that the content is fixed. This led to the same pair concluding that vertical viewport panning is even a useful feature for equalizing avatar height such that short and tall users can collaborate at eye level. This is a perfect example of the tension between physicality and reconfigurability, showing the need to familiarize oneself with these mixed metaphors. However, it shows that the utility of reconfigurability can be subtle but powerful.

Participants perceived MR whiteboard metaphors differently. Blended Whiteboard provides a mixture of whiteboard metaphors, which led to several differing interpretations and interesting focus-group discussions of the utility of Blended Whiteboard. In a discussion of canvas vs viewport navigation, Participant 10a stated *"I liked when I could see what she did"* (indicating a preference for the canvas mode), and 10b responded *"I can see the use of both"*. While most pairs favoured viewport navigation because it enables independent work, this pair worked mostly synchronously with turn-taking on every action toward the whiteboard. During their task of choice, they further remained in the side-by-side formation, using it like a physical smartboard. Pair 6 discussed the metaphor more explicitly. Participant 6b said they did not understand the need for zooming; *"you just walk close to the [whiteboard]"*, to which 6a responded with the opposing view that its interactions are similar to Miro, concluding *"It's like a 3D tablet"*.

6 DISCUSSION

The implications of this work are structured along themes related to the balancing between physicality and reconfigurability; 3C trade-offs (6.1), proxemics and f-formations (6.2), and whiteboard navigation (6.3).

6.1 The 3C theoretical lens reveals trade-offs between physicality and reconfigurability

To unpack the 3C trade-offs, we review the implications of the user study through the lens introduced in Figure 3.

Coordination vs. cooperation. The first implication from our study is that there are trade-offs related to the use of different f-formations for MR whiteboard collaboration. The user study revealed that, while the side-by-side formation provided more intuitive **coordination cues** (facilitating natural bodily turn-taking and attention switching), the face-to-face formation enabled new **cooperative actions**, such as working independently on the same whiteboard area simultaneously and better maintaining both partner and content in view. While these insights differ from prior accounts of traditional f-formation patterns (i.e., in co-located interaction, face-to-face formation is rarely used for cooperating) [23], it is consistent with the similar VR study by He et al. [17]. This suggests that users adapt their facing formations to fit the affordances and constraints of VR/MR technologies.

Communication vs. cooperation. Our study further extends He et al.'s results in two ways; first, by offering detailed insights on the dynamic use of f-formations and transitions between them; second, by providing insights related to the details of immersive whiteboard applications. We show how the whiteboard navigation works in an interplay with the users' facing formations. The side-by-side formation was regarded as useful for discussing the whiteboard content with natural **communication cues for shared attention**, switching between person and task. However, the formation made **joint cooperation** difficult, especially because lacking partner awareness led to conflicts in the canvas panning, requiring more formal turn-taking to navigate the canvas. On the contrary, pairs often favored the viewport panning for its support for independent work, despite the increased number of avatar interferences. These interaction effects between f-formations and navigation modes clearly convey the tension, and they validate the need for the two first principles; to support switching between both f-formations (**Dynamic F-formations Principle**) and the two modes of navigation (**Dual-Mode Navigation Principle**).

Communication vs. coordination. Finally, observed system usage in the freeform whiteboard tasks revealed wide variation in how participants appropriated the system and techniques: some drew upon the physicality of a stable whiteboard surface, while others relied upon the reconfigurability for frequent switching between individual and group work. Interestingly, pairs that used the system as a real whiteboard mostly praised the system's **support for communication during closely coupled group work**, while those embracing the virtual aspects (e.g., independent zooming and panning) were more positive about the system's support for **switching to independent work**. This highlights that supporting a spectrum of usage, from minimal to frequent reconfigurations, accommodates a wider range of collaboration dynamics.

6.2 Proxemics and f-formations are redefined in blended reconfigurable workspaces

Our work poses new questions for proxemics and f-formation research. Consistent spatial relations are important [38], to which we specifically explore: *When* are they important? Can users navigate between multiple spatial reference frames and establish new temporary consistencies (e.g., repositioned or rescaled spatial relations) for the purposes of the task at hand? Arguably, these questions come as a consequence of our design choice to render avatars in a manner that preserves consistency in position and scale relative to the avatar user's local physical whiteboard. MR solutions could also decide to render avatars of remote users in a scale and position that fits more naturally into the local user's real space [7, 50, 63, 64]. These two approaches must not be mutually exclusive. For instance, future blended whiteboard systems could have avatar adaptation policies that would adjust postures for minor inconsistencies in scale and position to extend the situations where avatars remain at natural scale.

The interesting question then is when to switch between revealing the inconsistencies to users (as in, e.g., [43, 44]) and when to conceal them through avatar adaptation. Akin to prior work on multi-scale MR collaboration [43, 44], our work shows that users can *harness* blended space disparities for coordinating their collaborative work. For instance, scale disparities can, in fact, provide different kinds of awareness cues: while a scaled-down Alice avatar reduces the perceived physicality for Bob, it indicates detail work (i.e., zoomed in) while he is trying to gain an overview (i.e., zoomed out). However, as these disparities also reduce the sense of physicality, the **Reversible Transitions Principle** balances the underlying trade-off, for example Blended Whiteboard offers the "snap back to reality" action to render returning to physicality easily accessible.

6.3 Navigating MR whiteboards individually and together

While the study clearly implies a need for viewport navigation to support independent work, this mode of navigation also caused confusion, e.g., due to the sometimes unintended consequence that the partner's avatar gets repositioned when a user pans to the side. The same manipulation causes two simultaneous effects; in one continuous gesture, it both displaces whiteboard content and avatars. The metaphor was intended to be that a virtual viewport pan to the side is effectively the same as virtually moving in the blended space, reminiscent of virtual locomotion to adjust the space between avatars. However, the study results indicate that this interaction metaphor has room for improvement, as canvas panning often disrupted the partner's active task. Based on this issue, future research could investigate alternative solutions to implementing the **Dual-Mode Navigation Principle**. For instance, an idea inspired by our prototyping efforts was to leverage the concept of asynchronous reality (i.e., recording actions in one temporal reality and playing them back in another to achieve shared interaction across time) [6, 20, 28], but at a much shorter time scale. To resolve panning conflicts, temporary breaks in synchronicity between avatars could provide a new mode of content navigation that both preserves avatar positioning and enables independent navigation.

6.4 Limitations

First, adopting a theoretical lens of proxemics and the 3C model arguably leads to particular design choices and rich insights in the study data, but we do not claim our results to be exhaustive in solving the general tension between physicality and reconfigurability. Second, we conducted a diverse two-part study, one with a fixed task and the other allowing free exploration through a task chosen by the pair. However, the selected whiteboard tasks were somewhat limited in representing the full spectrum of whiteboard uses, both physical and virtual. Specifically, the comparative study focused on the task of affinity diagramming, which may have biased results towards parallel work. For instance, the need to physically touch the local whiteboard throughout most of the task required users to stay close to it. This may have caused the side-by-side formation to be less favorable as it was difficult to keep both partner and task in view. Additionally, due to study length constraints, users had limited time for training and the freeform task. This limits the range of use situations that we were able to observe with Blended Whiteboard. Consequently, some pairs did not utilize all system features during this task. Lastly, the mode switching design is preliminary and requires further design work. As a result, participants reported discoverability issues with these actions, which could be addressed in future versions to enhance usability. This lack of discoverability may have led some participants to use the system more like a real whiteboard without fully exploring its reconfigurability features.

6.5 Generalizability and future work

Although we have focused on two remote users with similar physical surfaces, our work has identified several new opportunities and challenges for how to generalize and scale the interaction design.

6.5.1 Generalizing to dissimilar environments. In the future of meetings, people will need to collaborate across dissimilar environments [15]. For instance, with different room sizes, the viewport changes may result in avatars clipping through the wall in one location and not the other. In more extreme cases, Alice might work from her office while Bob joins from a cafe. How can they engage in blended whiteboarding together? While Alice has a real whiteboard, Bob only has a cafe table. Can a small table and a large whiteboard be blended for effective cooperation? What would the disparity in surface orientation and scale entail for the rendering of avatars? Should we change to less physically embodied representations of users in such instances?

6.5.2 Generalizing to more than two remote users. The interaction model in Blended Whiteboard inherently supports scaling up the blended space by allowing users to reconfigure the spatial relations between whiteboard surfaces. In fact, its navigation principle enables breakout group formations, allowing three or more remote users to extend each other's surfaces rather than merely aligning them. For instance, imagine a group of six remote users splitting into two breakout groups: Three surfaces could be aligned with perfect overlap into one blended surface for one breakout group, and extending next to this surface, another set of three blended surfaces could accommodate the other breakout group. Each group would then have separate floor areas within which they could arrange in circular and semicircular f-formations around the whiteboard, typical for group arrangements [23, 31].

6.5.3 Generalizing to hybrid settings. A more challenging issue is scaling to hybrid work configurations [36, 37], e.g., two co-located and one remote user. Others have started exploring such hybrid settings for MR [10, 17, 19], yet this is in its early stages [5]. Hybridity entails a range of new challenges for MR, one of which is to support co-located interaction. Blended Whiteboard would currently work, assuming that co-located users could position themselves so that they would not see each other in physical space. An alternative could be to use diminished reality techniques to visually remove the co-located user and replace it with the avatar. However, while this would enable reconfigurable avatar relations, the spatial audio would then cause conflicts with the visual perception. As such, a more viable solution may be to simply regard the reconfigurability as infeasible and instead incorporate the physical constriants of co-located users. I.e., co-located users would be perceived by other remote users as sharing the same physical viewport, while co-located users would perceive each other naturally as real humans albeit wearing headsets. It is then a question for further study what the consequences of these asymmetries would be for whiteboard collaboration, e.g., issues of headsets occluding facial expressions, or the inequalities caused by differences in remote reconfigurability and co-located physicality.

7 CONCLUSION

This work has introduced the concept of Blended Whiteboard, a Mixed Reality system enabling remote collaborative whiteboarding. Blended Whiteboard combines the physicality of real whiteboards with the reconfigurability of virtual whiteboards to manipulate content and avatars' spatial relations.

The key takeaways from this work are as follows. Distributed MR whiteboards can harness the complementary affordances of real and virtual whiteboards to support effective collaboration. But when seeking to get the best of both worlds, tensions emerge: (1) real whiteboards support bodily coordination and turn-taking, while virtual whiteboards enable new kinds of joint cooperation; (2) with real whiteboards people can effectively manage shared attention, whereas virtual whiteboards provide more individual control for cooperating through parallel work; (3) real whiteboards support effective non-verbal communication cues, while virtual whiteboards provide more opportunities for coordinated switching between individual and group work.

To address these tensions, we have contributed three key MR whiteboard design principles: *Dynamic F-formations*—providing complementary whiteboard facing formations; *Dual-Mode Navigation*—providing shared and individual whiteboard navigation; and *Reversible Transitions*—providing easy access to return from reconfigurations. Insights from our user study highlight both the power of these principles and the challenges when it comes to resolving tensions between physicality and reconfigurability.

We believe that distributed whiteboard collaboration has the potential to be a transformative application, accelerating the broader adoption of Mixed Reality headsets. The Blended Whiteboard concept has shown a path for this MR application to combine the strengths of physical and virtual whiteboards, broadening the spectrum of capabilities in remote whiteboard collaboration.

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