Identifying Cognitive and Creative Support Needs for Remote Scientific Collaboration using VR: Practices, Affordances, and Design Implications

Monsurat Olaosebikan
Tufts University
Medford, MA, USA

Claudia Aranda Barrios
Tufts University
Medford, MA, USA
claudia.aranda_barrios@tufts.edu

Blessing Kolawole
Tufts University
Medford, MA, USA
Blessing.Kolawole@tufts.edu

Lenore Cowen
Tufts University
Medford, MA, USA
lenore.cowen@tufts.edu

Orit Shaer
Wellesley College
Wellesley, MA, USA
oshaer@wellesley.edu

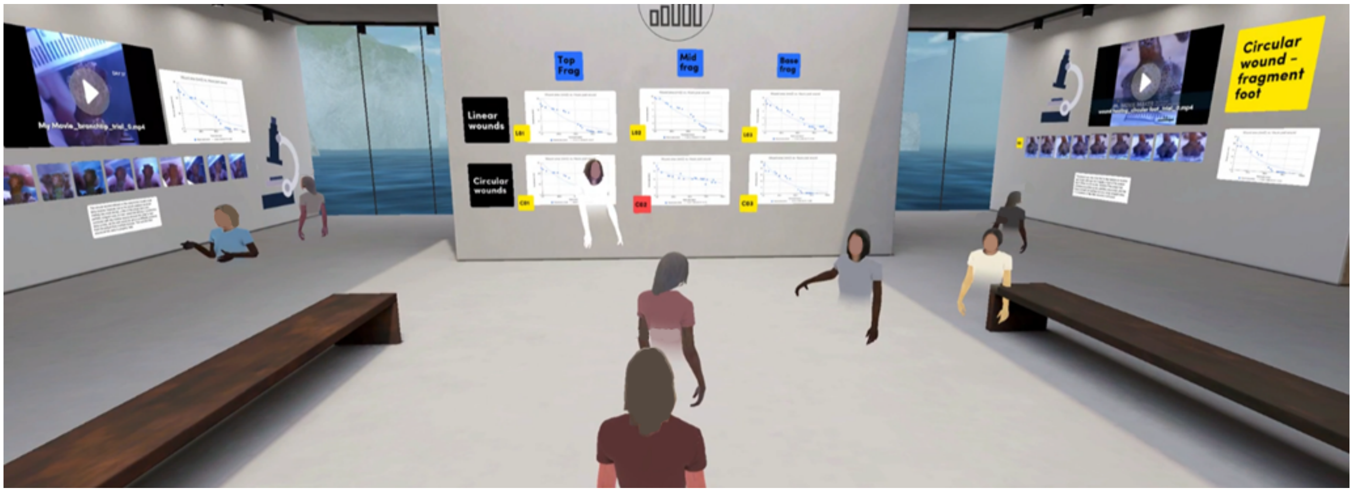

Figure 1: Scientists meeting in VR application Spatial to discuss their research data

ABSTRACT

Remote scientific collaborations have been pivotal in generating scientific discoveries and breakthroughs that accelerate research in many fields. Emerging VR applications for remote work, which utilize commercially available head-mounted displays (HMDs), offer the promise to enhance collaboration, through spatial and embodied experiences. However, there is little evidence on how professionals in general, and scientists in particular, could use existing commercial VR applications to support their cognitive and creative collaborative processes while exploring real-world data as part of day-to-day collaborative work. In this paper, we present findings from an empirical study with 14 coral reef scientists, examining how they chose to utilize available resources in existing virtual environments for their ongoing data-driven collaborative research. We shed light on scientists' data organization practices, identify affordances unique to VR for supporting cognition in a collaborative setting, and highlight design requirements for supporting cognitive and creative collaboration processes in future tools.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; *Interactive systems and tools.*

KEYWORDS

virtual reality, remote collaboration, scientific discovery, scientific data science, coral science

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1 INTRODUCTION

The COVID-19 pandemic has posed new challenges for collaborative scientific research, by disrupting travel and in-person collaborations, making them rare and uncertain for the near future. As a result, scientists and research initiatives have begun to explore and reflect on how research is currently conducted remotely and how remote collaborations could be enhanced in the future [2, 16, 71]. Scientific research requires creativity to generate new knowledge [27] from developing concepts and interpreting results to designing experiments. Scientists collaborate to build on each other's ideas to discover new connections. Emerging virtual reality (VR) applications for remote work, which utilize commercially available head-mounted displays (HMDs), offer the promise to enhance collaboration, through embodied and spatialized experiences [32, 47] allowing multiple users to simultaneously manipulate shared representations of data while making presence and actions visible to all users which could enable scientists to engage with their data creatively. They integrate reality-based interactions [24] such as gestures, spatial and physical manipulations, to offer a natural, intuitive, and immersive user experience, leveraging users' existing knowledge and skills of interaction with the real non-digital world such as naive physics, spatial, social and motor skills. The research area of immersive analytics [30] combines reality-based interaction techniques with data visualization and machine learning technologies to enable seamless data-driven collaborations (both co-located and remote). Immersive analytics, which utilizes VR technology, is thereby positioned to transform the ways in which people collaborate to explore, make sense, and generate new knowledge from large and complex data sets. However, while the display and interaction technologies required for implementing immersive analytics systems already exist, more fundamental knowledge of **how to design distributed VR environments to enhance scientific discovery** is lacking. Previous work has touted VR's potential for use in work situations [68] as well as for data exploration [21], data analysis [11, 18], urban planning [53, 72, 73], and knowledge retrieval [69], however, the use of VR for collaborative data-driven remote work is still in its infancy. There is little evidence on **how professionals in general, and scientists in particular, can and actually use existing commercial VR applications with their own real-world data for their day to day work**. To address this gap, we explore how emerging commercial HMD VR applications could be used to support remote scientific collaborations, and in turn inform the design of future distributed VR environments for enhancing scientific discovery. In particular our investigation focuses on the following research questions:

> **RQ1:** *How do scientists use the virtual environment to organize their data and themselves?*
> **RQ2:** *What affordances in VR provide cognitive support for scientific collaboration?*
> **RQ3:** *How can these affordances (RQ2) be expanded upon to provide additional cognitive support?*

To answer these questions we observed and interviewed interdisciplinary groups of scientists studying coral reefs collaborating remotely using commercially available HMD VR meeting applications. The scientists conducted their ongoing weekly research meetings using VR over a period of four weeks. Due to the complexity of corals and their environment, researchers in coral science work in interdisciplinary teams that include biologists, biochemists, computer scientists, and mathematicians. Such teams produce and study large amounts of data spanning biological, temporal and spatial scales. Thus, coral reefs represent an ideal scientific domain for exploring the use of VR for data-driven scientific collaboration. Our paper makes the following contributions. First, we expand the current literature on the use of immersive environments for data-driven collaborations by offering empirical evidence of *how* scientists utilize shared artifacts, embodied interaction, and spatial interaction in commercially available VR environments for conducting their ongoing scientific collaboration. Second, we identify affordances in VR for cognitive support during scientific collaborations and identify limitations in the currently available tools, and thus highlight unmet needs to address in the design of future tools. Finally, we synthesize design requirements for providing cognitive support for scientific collaboration in future VR applications.

2 RELATED WORK

Our work aims to expand the current literature on using VR applications for remote scientific collaboration and to provide design requirements based on our observations of teams using a commercially available VR application. Our work draws upon three areas: creativity and cognition in remote scientific teams, collaborative virtual environments, and affordance theory.

2.1 Creativity and Cognition in Remote Scientific Teams

Scientific research requires creativity to produce new knowledge [27]. Scientists engage in theoretical creativity when developing concepts, formulating research questions, and interpreting results and methodical-instrumental creativity when conducting experimental work [27]. Many scientific discoveries are the result of collaborations between multiple disciplines and institutions [12, 14]. However, many of these collaborations take place remotely due to distance and prohibitive time and money requirements needed to frequently meet in person. Fortunately, with advancements in technology scientists who are geographically distributed are able to collaborate remotely [16]. However, remote collaboration poses several challenges to a team: alignment of incentives and goals, awareness of colleagues and their context, establishing trust is difficult, and there is a lack of motivating sense of presence with others [35, 40]. Additionally, frequent use of technologies like videoconferencing can lead to fatigue [7, 36] and limits group cognitive processes to a 2D screen, instead of a physical space with access to walls, whiteboards, sticky notes and notebooks, thus depriving groups of cues, physical interaction, and body language that are beneficial for creativity and cognition [50].

In "A Theory of Remote Scientific Collaboration", Olson et al. discuss five factors that lead to *success* in remote scientific collaborations: the nature of the work, the amount of common ground among participants, participants' readiness to collaborate, participants' management style and leadership, and technology readiness

[39]. In her book *Extended Mind* [43], Annie Murphy Paul synthesizes findings from the fields of embodied, situated, and distributed cognition to propose a framework for "thinking outside the brain". Her framework draws upon Clark and Chalmer's seminal article titled "The Extended Mind" [17] to define thinking outside the brain as "skillfully engaging entities external to our heads—the feelings and movements of our bodies, the physical spaces in which we learn and work, and the minds of the other people around us—drawing them into our own mental processes." Meeting in VR could enable scientists to engage in extended mind practices - taking advantage of the spatial and embodied interactions facilitated by VR applications to 1) offload information into the world; 2) transform information into an artifact and then interact with it; 3) seek to productively alter one's state for improving mental labor; 4) re-embody information; 5) re-spatialize information; 6) re-socialize information; and 7) generate cognitive loops [43]. VR has successfully been used in other areas requiring creativity like generative design [65], content creation [22], and emotional reflection and communication [54] and is thus worth exploring further for supporting scientists collaborating remotely, as means to overcome some of the limitations of video-conferencing tools.

2.2 Collaborative Virtual Reality

Platforms like Mozilla Hubs, VR Chat, AltspaceVR, and Rec Room enable people to meet, create, socialize and play in VR. Researchers have designed several systems for collaboration in VR for architectural discussions [23], design [34, 55], creative tasks [42, 48], robotics [31], medical consultations [29] and telepresence [41]. New commercially-available collaborative mixed-reality tools have emerged to support work activities, allowing professionals to collaborate by providing a virtual environment for exploring data, interacting, and ideating. For example, Spatial [58] is a general purpose mixed-reality tool for creative team work, MeetinVR [33] is a tool for meetings, BadVR [6] is a data visualization and analytics platform, and Nanome [37] is a tool for manipulating and visualizing proteins. While there is a growing body of work on the use of social VR for education [44–46, 52] and on the challenges of authoring VR applications [5] little work has explored the use of social VR systems in real world professional settings for scientific research. Our work aims to expand the literature by providing insight into the work practices of an interdisciplinary group of scientists meeting in VR.

2.3 Affordances of Virtual Reality

The theory of affordance introduced by James Gibson was defined as "*the affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill*" [20] and later expanded on by Don Norman in the context of HCI to refer to "*the perceived and actual properties of an object that determine how the object could possibly be used*" [38]. Literature has shown that VR technology provides certain affordances such as the ability to enhance positive aspects of the physical world, recreate existing aspects of the physical world, and create aspects that don't exist in the physical world [59]. Some affordances found in virtual worlds such as Second Life (e.g. space, immersion, avatars) are thought to be native to the technology while others are "constructed" (e.g. avatar customization, instrumentation, virtual economies) [60]. Additional work has explored affordances in the context of VR games [28], learning [57], and perception [13]. Our investigation seeks to identify what affordances are available in current commercially available VR applications that are useful to scientists collaborating remotely and identify affordances that could be constructed to provide further cognitive support for scientists in their collaborative work.

3 EXPLORATORY STUDY OF CORAL REEF SCIENTISTS MEETING IN VR

We conducted an observational study where two interdisciplinary groups of scientists studying coral met on a weekly basis using the VR meeting application Spatial[1]. We chose Spatial specifically because participants are able to import multiple data formats (3D, pdfs, images) to give the interdisciplinary teams of scientists the ability to share the different kinds of data generated in coral reef research. In Spatial, they are also able to create realistic avatars that resemble themselves, which could be important in a professional setting for promoting trust [70] and seriousness [26] compared to using cartoon avatars. It is important to note that most existing VR meeting applications, such as MeetinVR [1], Glue [51], Engage [3], and Rumii [4] offer features similar to those supported by Spatial.

3.1 Procedure

We recruited 14 scientists studying corals (9 women), age range between 23-64, who were split into two groups of 7 participants each based on existing collaboration groups. Participants were collaborators on a funded coral science project, who were already meeting on a regular basis using Zoom, and differ in their core academic discipline and academic title. Participants (see Table 1) were recruited by email using the funded project group's email list and received an Oculus Quest headset as compensation. Each group met using the VR application Spatial over a period of 1-2 months for a total of 4 meetings each. All participants used an Oculus Quest 1 or 2 device to attend the meetings.

Each meeting in the virtual environment lasted 45mins - 1hr followed by a 10 minute post-questionnaire and a 20 minute group discussion on Zoom. In the first meeting, participants were given a pre-questionnaire, a tutorial on how to use Spatial, followed by a brainstorming session where the participants discussed research areas of interest and research questions they wanted to explore during the remaining 3 meetings. Subsequent meetings were left up to the participants to structure how they saw fit. In the last meeting, participants selected to use Nanome[2], a VR application for molecular design, in addition to Spatial to explore protein molecules. In each meeting, a member of the research team recorded the meeting from a 1st person perspective in VR and a second researcher recorded the meeting from a 3rd person perspective using the Spatial web app and the Nanome desktop application. Participants were also asked to record the meeting from their headset to capture their point of view.

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[1] https://spatial.io/

[2] https://nanome.ai/

The pre-questionnaire asked if participants had prior experience with VR and what their expectations were. The post-task questionnaire collected the following information: demographics, spatial presence (using MEC-SPQ [66]), self-efficacy and collective efficacy (based on [10] and [39]), and open questions about participant's experience in each meeting. During the group discussion, which followed each meeting, we inquired about what functionality the participants wished the virtual environment had, what challenges they faced while using the virtual environment, how they compare their experience in VR with that of traditional video conferencing software, how they felt VR influenced the way they collaborated, and how they used the virtual environment to explore their research data. In this paper we focus on the data collected from the open questions and group discussions.

Table 1: Demographic Information of Participants

ID	Title	Research Area
P1	Assistant Professor	Marine Biology
P2	Assistant Professor	Computer Science
P3	Research Assistant Professor	Microbiology
P4	Graduate Student	Computational Biology
P5	Graduate Student	Computational Biology
P6	Graduate Student	Coral Biology
P7	Research Scientist	Computational Biology
P8	Postdoctoral Fellow	Marine Biology
P9	Associate Professor	Mathematics
P10	Professor	Mathematics
P11	Associate Professor	Nanotoxicology
P12	Associate Professor	Biochemistry
P13	Postdoc	Biology
P14	Professor and Director	Biomedical Engineering

3.2 Data Analysis

We transcribed each group discussion and conducted a thematic analysis [15] to analyze the transcripts from each group discussion and the open responses to the questionnaires. We first reviewed all data and generated 25 initial codes, then through iterative discussion added 5 additional codes, for a total of 30 codes. A codebook was created to answer RQ2 and RQ3 with operational definitions and examples for each code. Then, two coders used this codebook to code the data and added additional codes as needed for a total of 34 codes. Inter-coder reliability was established based on 100% of the data with 97% agreement. Afterwards, codes were collated into 12 themes and then further collapsed into 9 themes through an iterative discussion among the research team. For example, the following codes: facial expressions, hand raising, nodding, pointing, presenting a talk, visual feedback and visual cues, communication and turn taking were collated into the theme *Lack of Non-Verbal Cues and Communication Challenges.* Videos of the meetings were analyzed manually to identify meeting strategies and spatial organization strategies. The researchers then discussed repeating patterns as a group.

4 FINDINGS

In this section, we provide empirical evidence of how scientists utilized a commercially available VR environment for conducting remote scientific collaboration. We identify the data organization and meeting strategies they used, affordances they perceived in the environment, and limitations of using the environment for remote work and thus opportunities for constructing additional affordances in future tools to better support remote scientific collaborations, and in turn enhance scientific discovery.

4.1 Meetings Overview

The scientists created and interacted with many artifacts over the course of multiple meetings. Artifacts included uploaded images, videos, pdfs, 3D models, scribbles in space (doodles), web browser windows, slack channels, and sticky notes. In meetings, participants used all of these artifact types to discuss their research. Group A participants uploaded artifacts during the meetings while Group B participants created the room and uploaded/created artifacts prior to their meetings. Each of these artifact types were used in several ways. Images were used to share text paragraphs, graphs of data, pictures of experiment outcomes, and as visual indicators to separate sections of data. Sticky notes were used as titles and labels for data and as a mechanism for leaving comments, questions or giving feedback. Pdfs were used to share research papers and descriptions. Videos were used to show experiments in progress and 3D objects were used for proteins.

4.2 Spatial Organization Strategies

We identified three different spatial data organization strategies used by the scientists in the virtual environment: 1) anchoring data to different walls in the room 2) arranging data in a circular format in space, and 3) using a specific area of the room as the focal point of the meeting.

4.2.1 *Anchoring data to walls.*

In this organizational scheme scientists used the walls as anchoring points for their data. Each wall fell under a particular theme: overview, background, experiment, comparison, or summary. For example, in the room depicted in Fig. 2, the scientist used a different section of wall for each wound healing experiment they conducted. For each experiment, they displayed a description of the experiment, time lapse video, images from the video and a graphing of the measurements they took. On separate walls they had an overview of the research project as a whole and background information on wound healing. To facilitate comparisons of all experiments they had a separate comparison wall where they duplicated the graphs seen in each individual experiment side by side. Additionally, they had a summary wall where they summarized their findings, proposed future directions and left space for other participants to leave feedback or ask further questions about the research.

4.2.2 *Circular Arrangement of Data.*

In this organizational scheme the scientists arranged their data in a circle in space (see Figure 3). The content of each section of the circle was very similar to that of the anchoring data to walls organization. Each section was either an overview of a project, background information or experimental data.

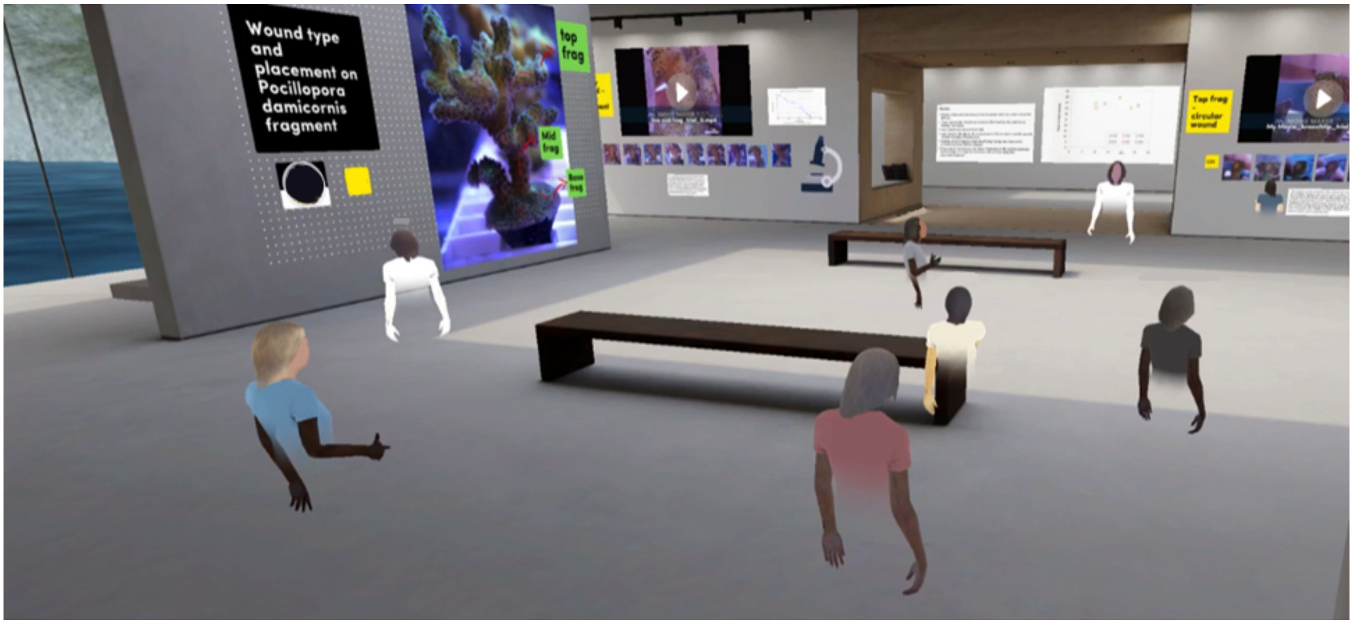

Figure 2: A meeting room with data anchored to the walls (Group B Meeting 2). The walls in the back show timelapse video, images, and a graph of the wound size change over time from wound healing experiments on different sections of coral.

Figure 3: A meeting room created by P13 with data from a coral polyp bailout experiment in a circular arrangement (Group B Meeting 3).

4.2.3 *Focal point.*

Scientists using this organizational scheme usually had one artifact they were focusing on for the entirety of the meeting. This could be a research paper in progress or a presentation for a practice talk they were giving in the virtual environment.

4.3 Meeting Organization Strategies

We identified four different meeting styles used in the meetings: 1) guided tour 2) exploratory tour 3) artifact centric and 4) seminar presentation.

4.3.1 *Guided tour of data.*

This meeting style was characterized by a participant giving an initial introduction of the data in the room followed by a guided tour around the room explaining each of their datasets. The data in this meeting style is characterized by a wall anchoring organization of the data. An example of this is Group B meeting 4 (see Fig 4) where P10 started off with an introduction of the available data in the room and talked about the process they took to develop their mathematical models. Then P10 and P9 led a guided tour to each of the walls in the room to explain the models on the wall and discussed their ideas with the group and how they might transfer the models to corals.

4.3.2 *Exploratory tour of data.*

In this meeting style, after the leader of the meeting gives a general introduction of the space, they allow other participants to explore the data in the space on their own while they are centrally located and answer any questions people

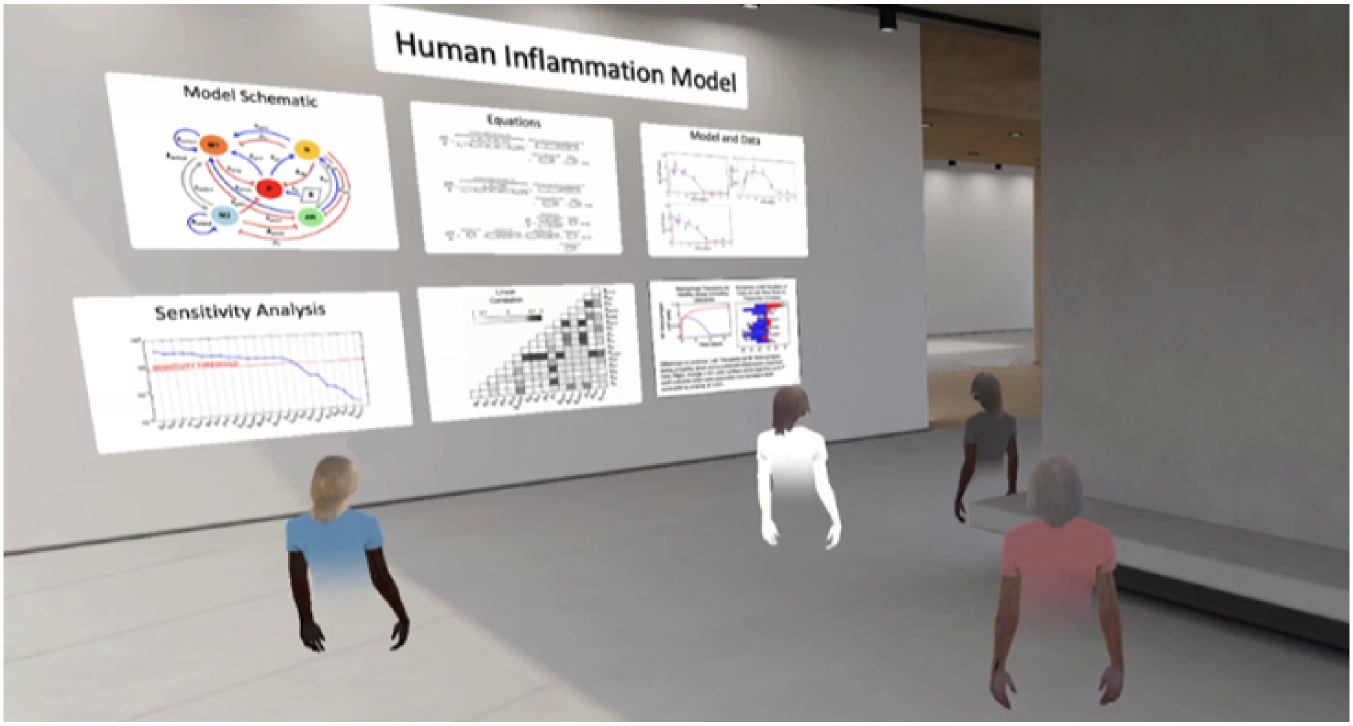

Figure 4: Participants follow P10 as they give a guided tour of the mathematical models on walls in the room (Group B Meeting 4)

have as they explore. Wall anchoring was the main organization method for data in this meeting style. The discussions in this meeting style were guided by the questions and ideas presented by the participants exploring the data. An example of this is Group B's 2nd meeting. P8 created a new room using the Gallery environment and designed the space to display data they collected from the wound healing experiments they had been conducting on corals (see Fig 5). The walls of the room included time lapse video and pictures of corals from their lab and graphs of experimental data collected during the experiments. In the beginning of the meeting, P8 gave a brief introduction of the space and used hand gestures to point out where specific pieces of data were located. At the conclusion of the introduction they pointed out a specific place where they wanted everyone to convene to discuss their thoughts and ideas after exploring the data. Participants then started exploring the data in the space and asking questions directed to P8. For some questions P8 directed the asker to follow them to parts of the room and used the data on the walls to answer their questions. P8 was clearly the leader of this meeting, however much of what was discussed was guided by the questions asked and ideas presented by other participants who were viewing the data. At the conclusion of the meeting participants used sticky notes to write notes and next steps for P8 to review later.

4.3.3 Artifact Centric. In this meeting style, participants spent the majority of the meeting focused on a single artifact, for example, a pdf of a research paper. This follows the focal point spatial organization of data mentioned earlier. Group A's 2nd meeting is an example of this (see Figure 6). In that meeting P2 gave an overview of a paper that was a work in progress with other participants in the meeting, some of which were contributors to the paper and others who were not. P7 also asked for feedback from the other participants about a couple of figures that were going to go into the paper that P2 was giving an overview about. In Group A's 4th meeting participants discussed a protein molecule in Nanome (see Figure 6).

4.3.4 Seminar Presentation. In this meeting style, one of the participants gives a talk aided by slides while the others listen. This meeting style usually falls into the focal point data organization category with the presenter and slides being the focal point at the front of the room. Group A's 3rd and 4th meeting exhibited these characteristics (see Figure 7). In one of these meetings P7 gave a practice talk for an upcoming conference and in the other P2 gave a research talk. Both meetings took place in the auditorium environment.

4.4 VR Affordances for Cognition

In this section we highlight affordances scientists observed while using VR for scientific research collaboration based on their interview and post-questionnaire responses.

4.4.1 Focused Engagement. One key affordance of meeting in VR is that outside distractions (emails, slack) are removed from the virtual environement enabling participants to focus completely on

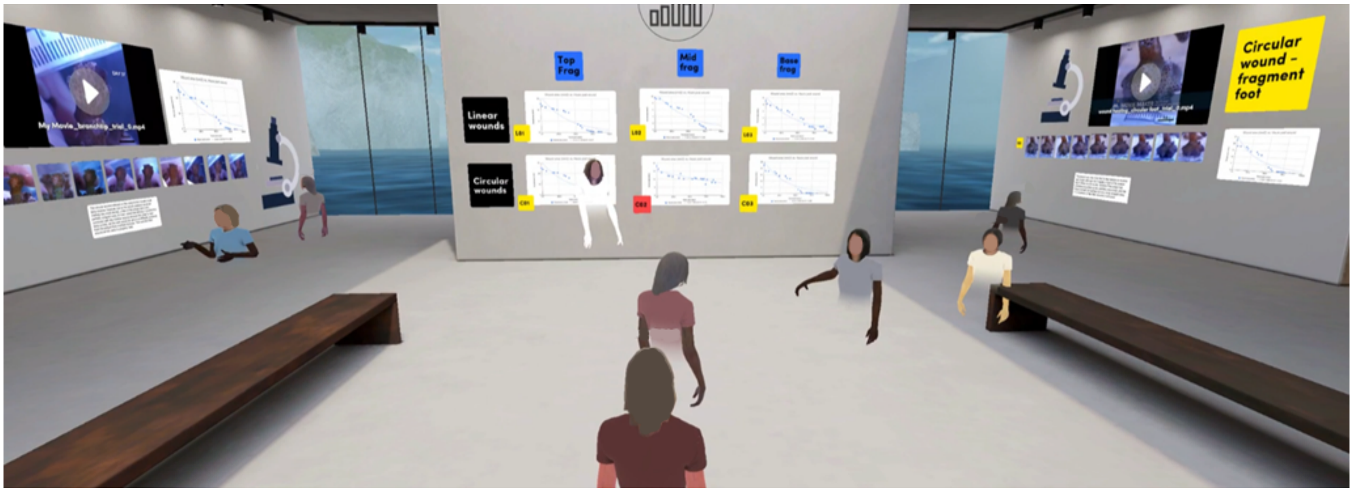

Figure 5: Participants explore data on wound healing in the space at their own pace, while P8 the creator of the room answers questions in the center of the room (Group B Meeting 2).

Figure 6: (Group A Meeting 2) Participants meet and discuss a research paper that is in progress (Left). Participants gather around a protein molecule to discuss (Right)

the meeting at hand. 5/14 participants expressed this sentiment. For example:

> P4 (Graduate Student): *I really like attending VR presentations as opposed to Zoom ones - there is more sense of community and it is easier to focus.*

> P9 (Associate Professor): *I would definitely say that I forgot where my computer was... let alone trying to check my email, which was great.*

> P1 (Assistant Professor): *If I was going to go to [...] a seminar virtually I would prefer to do it, the way it was done today [...] I felt much more immersed and connected to the presentation and focused on it*

In an environment mostly absent of distractions participants were able to remain engaged for longer periods of time (6/14). For example:

> P13 (Post-Doc): *I am a biologist and had trouble following & being captivated by the mathematical modeling content. However I think I zoned out much less than I would have if it had been a "regular" research meeting on zoom.*

> P10 (Professor): *The way I interact with science is more immersive and engaging.*

4.4.2 Presence. Participants felt they were actually present in a face to face meeting. 3/14 participants commented on feelings of presence. For example:

> P3 (Research Assistant Professor):*The meeting was great and once you are in VR environment, you blend in and feel almost real.*

> P7 (Research Scientist): *In a live talk you sort of have to do this swing your head thing where you're looking at your talk, where it is and then you're looking at the*

Figure 7: (Group A Meeting 3) P7 gives a work in progress conference talk to the group

> *audience and in VR [...] I found myself doing the same thing which was great because I was seeing the audience, and so it sort of made it feel more real to me, I mean for me, this was much closer to live talk than a zoom talk*

4.4.3 Data Exploration Autonomy. Another key affordance was the freedom to explore. In the virtual environment participants were able to explore research data on their own and as a group. This is distinctly different from a video-conference meeting where there is a sequential presentation of data controlled by a single speaker. Participants appreciated the autonomy this gave them to take in information at their own pace and redirect discussions when more context is needed. 5/14 participants commented on this aspect, for example:

> P10 (Professor): *I think it made for a really effective meeting because we could wander around, everything was on the walls, you could see it kind of all at the same time [...] Like if I wanted to kind of go back and look at something while you were talking I could just hop over and see it rather than having to interrupt you and say, can you go back three slides.*
>
> P12 (Associate Professor): *It is much better than one appreciates I mean previously, I was always comparing it to you know if I had two computer screens, I can have 10 windows open in parallel and flip around with them, and so that way I can easily go back to something that I haven't seen but that requires that you have access to the files right, whereas here someone else can be the owner of the file and have uploaded it and you can still go back to it as if you owned it I think that's one of the major advantages*

4.4.4 Spatial Arrangement. Participants noted that the ability to arrange and compare data using the larger space afforded by the virtual environment was beneficial.

> P12 (Associate Professor): *I think the major advantage I realized in the mathematical modeling vr room is to look at multiple things side by side, so you know how you have six slides all in one and it's so easy to go back and forth between different slides*
>
> P10 (Professor): *Yeah I think being able to put things adjacent to each other in ways that it's hard to do in a static environment, that's going to be really cool*

Another example of this aspect, is this conversation between a postdoc and professors about a time lapse video of an experiment that they placed in the room augmented with static photos of key timesteps laid out in sequence (See Figure 2):

> P8 (Postdoctoral fellow): *you know how I put the photos up, but I also had a video, which one did you think worked the best for you to sort of process the information?*
>
> P9 (Associate Professor): *I watched the video first, but then I didn't want to stop and pause it so it was nice to then look at the pictures and be able to kind of slow-mo move my eyes across it.*
>
> P8 (Postdoctoral fellow): *So it wasn't like redundancy?*
>
> P9 (Associate Professor): *No, when I watched it originally there were things that I didn't pick up on, but I got the idea of how it was moving*
>
> P10 (Professor): *yeah seeing the changes relative to the previous time step in the video is helpful, it was really nice to be able to look at the individual photos and see the shape change*

4.4.5 Physical Manipulation. Finally, participants noted that being able to "hold" and manipulate data made it easier to remember and think about. Two participants commented on this aspect:

> P1 (Assistant Professor): *I'm much more of a holding my hands write it down visual learner so if someone hands me something I'm going to remember it more than just the page [...] I can't remember stuff otherwise*

> *so somebody handing it to me makes a much different impact than just looking at it*
>
> P10 (Professor): *For us as modelers, having components of a biological system that you can move around,[. . .] if it seems even more interactive and physical that you could really get a handle on, like this signal influences this cell type and then how you make all those connections together could be a new way of building models collaboratively*

4.5 Opportunities for Constructing Affordances

In this section we identify ways in which meeting in VR felt limiting for the scientists as opportunities to create new affordances in future tools.

4.5.1 Steep Learning Curve. Participants expressed that learning to use the virtual environment had a significant learning curve. In particular 9/14 participants reported that the learning curve prevented the group from engaging in meaningful discussion in their first meetings. There is a general agreement that there is a significant setup cost for joining or facilitating a VR meeting. For example:

> P9 (Associate Professor): *I think the interface is good, I think there's a little bit of a learning curve to get to the point that we were actually talking about research ideas*
>
> P10 (Professor): *There is a steep learning curve where everyone needs time to adjust to the new settings, controls, etc. Once we all got used to it, we could have more productive conversations and look at different research questions.*

For future systems to be more widely adopted the applications need to introduce perceived affordances that guide the user and make the interface easier to use, reducing friction and the cost of facilitating and joining VR meetings. To grow the adoption of VR among professional users and data-driven teams there is a need for affordances and interaction paradigms that are consistent across different applications, allowing users to explore and experiment with different tools with minimal barriers to entry.

4.5.2 Limited Whiteboard and Note-Taking Functionality. Participants noted that the tools for whiteboarding and note taking in the virtual environment were limiting. In Spatial, sticky notes doubled as a whiteboard that could be written on with a marker and could be positioned anywhere in the room or on a sticky board at the front of the room. Users are able to type text on the sticky note, draw with differently colored markers, sizes, and change its background color. However, sticky notes are only editable by one person at a time. Participants wanted a whiteboard that affords use by multiple users at the same time similar to ones available in classrooms and office spaces. Participants emphasized a need to be able to build off each other's ideas and to move text around freely:

> P1 (Assistant Professor): *I think often we want to build off of each other, what we're saying and we get triggered by some idea or you know excited by some idea, and then we wanted to tweak it in some way, and it would be a lot easier to just be able to do that.*
>
> P2 (Assistant Professor): *Make it mirror as closely as possible a whiteboard in my office, anybody can grab a marker and start writing on some part of it*

However, they also noted enhancements that would make a VR whiteboard better than classroom ones, including making drawings more legible, and auto-capture of drawings at different intervals. They also noted that a central repository of all sticky notes and the ability to refer back to what was discussed in previous parts of the meeting post-meeting would be useful. For example:

> P1 (Assistant Professor): *It would be neat to have like timed auto capture of things too, and I think with the recordings, we have some of that but for example, they have like the smart whiteboards right where you press the button and it scans the whole thing....Something like that,where you know every five minutes there's a capture of that so that, as you draw over it,or erased or something if you do an accident, then you have versions of that.*
>
> P11 (Associate Professor): *With the group someone can be designated to take minutes but that's not the same as writing, you know, your thoughts of what you know, what occurred to you, while the discussion was going on. [...] I'll go back to some recorded meetings but like that's another thing is maybe, is there a way to timestamp then so that I know okay, I want to revisit these 10 minutes versus have to sort through the whole hour.*
>
> P12 (Associate Professor): *it would be nice to have both options that you can put sticky notes wherever you want them, but you also have the ability to have some kind of central repository.*

Another aspect that participants felt frustrated with is the inability to write personal notes or quickly write down a continuous stream of thoughts as one would on pen and paper or with a physical keyboard. Future tools should afford personal note taking as note taking is a critical cognitive support tool for generating ideas and expanding research into new directions [43].

> P11 (Associate Professor): *I still haven't quite moved to electronic unless I'm in front of my computer and can type the notes. Otherwise tablet, you have the writing feature, paper and pen, you have the writing feature and it's just a lot faster, more efficient to capture your thoughts, because if people are talking really quickly I find handwriting's the only way I'm going to capture what I wanted to see from that conversation and so there were times when we were having very good discussion [. . .] and I want to take note and I don't know how to do that [...]*

4.5.3 Lack of Non-Verbal Cues and Communication Challenges. Participants noted the lack of non-verbal cues such as facial expressions, nodding and other small gestures. They expressed a need for cues to be perceivable in the virtual environment. The following snippet from a post-session discussion illustrate this point:

> P1 (Assistant Professor): *[...] my brain wanted some sort of visual feedback from from the group, I felt bad about not looking at people, while I was talking to them and I wanted that visual feedback in my brain I think of like how the discussion is going that I didn't necessarily anticipate.*

Future tools should consider making affordances for turn taking and engagement more explicit and perceivable. It was hard for participants to gauge engagement in some areas (e.g. while giving a talk) and easier with others (knowing if someone is fully checked out or multi-tasking). They expressed difficulty with perceiving when someone wanted to speak which made taking turns difficult and accidentally interrupting or speaking over others common. For example:

> P11 (Associate Professor): *Engaging in conversation in the VR environment is similar to videoconferencing and it would be interesting if the technology advanced to where the experience would be closer to simulating the in person environment where one can have side conversations or better gauge when there is an opening to speak.*

> P7 (Research Scientist): *one sort of downside, compared to live, which is that you can't see engagement from people's eyes*

> P5 (Graduate Student): *The bright side with VR is that if someone is really checked out you probably can tell, because they're like just moving the character around looking at like the ceiling, instead of your presentation or instead of at you*

4.5.4 Friction with Creation Tools. Participants expressed frustration with the available tools for creating a room with their own data. Four participants (3 different rooms) created a virtual room and filled it with their data prior to the scheduled meeting. Challenges they faced creating these rooms included difficulty placing data artifacts precisely where they wanted them, friction from having to use the desktop app to first upload all data and then having to position it from within the headset, and not having access to primitives like a text labeling tool or 2D shapes (arrows, squares, circles). Incorporating affordances for simplifying the process of arranging data spatially could enable users to quickly share their thoughts, ideas and progress. VR affords defying the laws of physics, which can be used to a users advantage, for example, data artifacts could be made snap-able to any wall or surface unlike the real world where you might need glue. In the words of participants:

> P8 (Postdoctoral fellow): *I found it tricky to set up the room, because it's hard to place things exactly where you want when you're using the desktop controls, [. . .] it's a two step process, so first, you have to set up, upload everything on your desktop and then you have to place the things in the space that you want to use.*

> P9 (Associate Professor): *We need a place-on-the-wall button [...] it's almost like you need the walls to actually be walls right so if you push it to the wall it stops at the wall right*

> P12 (Associate Professor): *For me, it was pretty tricky because these labels I had there's no way to upload text and so I had to type manually each of these labels and then because there's so many images that are close by you have to place them on the desktop version close enough so that when you go into VR you know where it is, and because you don't have a true 3D experience on the desktop when you move things around it depends really a lot on how your other text is positioned so, then you know, on your screen, it looks like it's close, but actually in 3D it's actually far away*

Another limitation participants faced was not being able to quickly find and import files they are interested in from within the virtual environment. For example, a research paper that became relevant during discussion. Participants wanted a stronger link between their desktop files and the files accessible to them in the virtual environment.

> P8 (Postdoctoral fellow): *Once you're in the virtual world, while we're having the discussion if we think, oh, and there's this paper or this other thing because discussion has led you to that it would be interesting to be able to add more to the data that you're discussing.*

> P2 (Assistant Professor): *Well clearly you know we wanted to bring in something that's very technical and domain specific with, namely a PDB file right and we couldn't.*

> P11 (Associate Professor): *I have to be off the headset on my computer, upload the file, put it on the website application and then go into the VR setting, and it feels like there's too many steps*

Finally, participants wanted to be able to create interactive visualizations or have a way to add interactivity to traditional slides. Functionality for adding interactivity could afford deeper discussions into the research being discussed and shed light on new ideas, leading to new insights.

> P8 (Postdoctoral fellow): *It would be interesting to have interactive images, [...] when I created the first room I had this initial image of the coral with the different wounds, and then I created the little buttons where when you click on that when you touch that button it brings out all the photos of that wound through the healing and the video and then you went and clicked on the wound on a different part of the coral and give you all that data, but this is not a feature in a virtual space, which is weird because it's meant to be interactive but then you're limited with the amount of interactivity that you can include*

> P2 (Assistant Professor): *I wish I had a way to easily jump to a VR representation of the visualizations embedded in my slides.*

5 DISCUSSION

Our findings shed light on how groups of scientists utilize existing virtual environments for facilitating data-driven collaborative research. We highlighted the meeting organization strategies used by the scientists to conduct different research activities and identified data organization strategies utilized in the virtual environment. We found scientists recognized and engaged with several affordances in the environment: focused engagement, presence, autonomy to explore data, and direct 'physical' manipulation of artifacts. However, we found that existing tools have several limitations that could be improved with new affordances to reduce the learning curve, improve whiteboarding and note taking functionality, improve communication, reduce the friction involved in using the tools for configuring the virtual environment, and reduce barriers for importing, placing, and organizing data artifacts. Following we reflect on how these affordances seem to support cognition.

Participants were able to share rich artifacts (timelapse videos, graphs, mathematical models) with which group members had the autonomy to engage individually, leading to "better, richer theoretical discussions" [39]: "*here someone else can be the owner of the file and have uploaded it and you can still go back to it as if you owned it I think that's one of the major advantages*". Participants arranged these artifacts in the virtual space by applying different strategies to organize the data - taking advantage of a space large enough to facilitate physical navigation (e.g. see Figure 5). Participants then explored the space drawing upon their natural navigational skills. Spatial navigation has shown to promote making new connections, as people are innately better at spatial thinking than abstract thinking [64]. Prior work exploring affordances of virtual worlds (e.g Second Life) categorized "affordances of the environment" into space which provides potential for movement, place which creates context for an activity and landscape which provides context for place through variations in terrain and geographical features [60]. Our work provides empirical evidence that the affordances of space, place, and location extend to VR environments and how scientists can benefit from the cognitive support afforded by these affordances to organize and explore information: "*if I wanted to kind of go back and look at something while you were talking I could just hop over and see it rather than having to interrupt you and say, can you go back three slides*." Our participants had a number of environments (places with landscapes) to choose from in Spatial and remarked how the setting (auditorium, boardroom, boardroom with round table) impacted their attention and ultimately their discussions: "*I felt much more immersed and connected to the presentation and focused on it*". Past research has explored using large or multiple displays to offload information [49] and trigger spatial memory and reasoning [8, 9, 25, 61, 62], however, having space for very large (wall-size) or multiple displays that allow for physical navigation is uncommon in a personal office, home environment, and in many research labs. VR environments allow users to benefit from spatial interaction on large surfaces even when their physical space is constrained promoting creative thinking.

Exploring shared artifacts in the virtual environment allowed participants to establish common ground around collected data such that they could engage in both theoretical and methodical creativity [27]: "*[...] as modelers, having components of a biological system that you can move around,[...] if it seems even more interactive and physical that you could really get a handle on, like this signal influences this cell type and then how you make all those connections together could be a new way of building models collaboratively*". The physical affordance of being able to manipulate and rotate objects is thought to underlie problem solving because it engages our visuospatial abilities [56, 60]: "*I'm much more of a holding my hands write it down visual learner so if someone hands me something I'm going to remember it more than just the page*". An additional way in which VR affords supporting thinking is by removing distractions normally available when using video-conferencing tools like email. The VR environment enabled participants to focus longer, especially in cases where their focus is required most. For example, learning from a collaborator in a different discipline where a shared understanding will allow for effective collaboration. The VR environment also removed the barrier of needing to have a polished presentation that flows in a linear format in order to present it to collaborators. Instead, scientists created a room and shared their data "as is" for quick discussion with the group, allowing for common ground to be established earlier in the collaborative process. Taken together, our findings demonstrate that using VR, scientists were able to transform their limited physical space in the real world into a thinking space with numerous walls to offload and externalize information, thereby extending their thinking [43].

Our findings illustrate that by affording reality-based interactions, which draw upon users' perception of naive physics as well as their body awareness, skills of navigating and altering their surroundings, social awareness and skills [24], VR meeting applications presents opportunity for scientific collaborators to extend their collective minds. As a technology, VR has matured significantly from its earlier days, however, in terms of readiness to be adopted by scientists for scientific collaboration there is still much room for improvement as demonstrated by the limitations we identified earlier. The design requirements we outline below offer a path forward towards making this technology ready for regular use by scientists for data-driven collaboration.

5.1 Design Implications for Designing VR Support Tools for Remote Scientific Collaboration

Based on findings from the preceding sections we synthesized the following requirements for the design of future VR tools for collaborative scientific discovery.

DR1: Granular control of the environment. Scientific collaborations consist of different activities ranging from brainstorming, to reviewing and comparing artifacts or processes, to sharing procedures and findings. We found that scientists require granular and effective means for controlling and altering their environment to support different activities. Some meetings might transition from artifact centric to a seminar presentation so there is a need for a seamless transition between settings, for example from a round table to an auditorium configuration. Such transitions can utilize the embodied nature of the space, allowing users to "walk" to an adjacent room. Users also need to easily alter their environment in order to spatialize information - organize the information on surfaces and walls so that it can be explored through physical navigation.

DR2: Rich and diverse communication channels. Users expressed a need for a variety of communication channels both public and private. For example, participants want to be able to ask a question but not interrupt the current flow of conversation, or to share a thought privately with another individual. Traditionally, chat boxes have been used in online meetings for this purpose, however, another alternative could be for users to create ad-hoc private spaces for small group discussion or side conversations. Users should be able to define individual and sound boundaries in such spaces. For example, this can be useful for the exploratory tour meeting style where participants explore the room on their own and form groups around areas of interest. Finally, there is a need to enhance communication by supporting rich non-verbal signals such as hand gestures, head nodding, or gaze. Users also need to identify when another user wants to speak, so making cues such as hand raising and nods perceivable even when someone is not in direct line of sight is important.

DR3: Robust and fluid whiteboards, annotation, and note taking. Users need whiteboards for developing and synthesizing ideas, which allow them to write and sketch legibly, while collaborating fluidly. This entails allowing users to work together in real time, extending or refining ideas on the board. In addition, users need support for collaborative writing and editing of documents, as well as for annotating existing artifacts (documents, images, videos, charts). Finally, users need to engage in continuous personal note taking, which include text, images, and sketching. Personal notes should remain private and be integrated into their regular digital notebooks. To allow for robust and fluid whiteboards, annotation, and note taking, future tools will need to provide means for both high text entry rate and free form sketching, as well as a variety of form factors for writing and sketching which include boards, notebooks, sticky notes, and documents. All writing and sketches should be exported and accessible after the VR session.

DR4: Efficient and insightful meeting minutes. Users need a multimodal summary of the meeting which includes the dialogue, artifacts produced (e.g. charts, post it notes), spatial arrangement of artifacts, and the path one took to explore. These summaries could be created by combining user generated notes, annotation, and automated capture. Since users rarely want to review an entire meeting from beginning to end but rather revisit key points, we anticipate using AI to produce a summary of the meeting. Such summary could be extracted based on audio and visual activity analysis, combined with text analysis [19] to allow users to efficiently browse, find, and access important artifacts or insights.

DR5: Seamless data integration. Users need to be able to seamlessly find, access, import, and manipulate data directly from the virtual environment. This means that users should be able to access their own files, shared storage systems, or the web, to retrieve relevant data upon request during a VR session as well as prior to and following the session. Relevant scientific data consists of heterogeneous file formats ranging from generic and popular formats such as pdf, video and and image files, to domain specific such as FASTA for genetic sequences, pdb and mmCIF for 3D proteins, and GIS data for monitoring reef conditions over time. To facilitate seamless data integration, future tools will be required to optimize the upload and storage of large files, in addition to supporting the display, editing, and annotation of the various file formats.

DR6: Physical manipulation of artifacts. To facilitate deep insights, it is important to transform data into concrete artifacts, which allow for rich "tangible" interaction. Such interaction might consist of grabbing, rotating, moving around, labeling, tweaking, and even '"feeling" (using tactile feedback) an artifact (e.g. a coral). We found that, where possible, users sought ways to directly interact with information artifacts, and require that various artifacts such as visualizations, videos, and images will allow for physical and spatial interaction. Turning interaction with data into embodied and sensory experience, could allow users to examine and synthesize information in new ways [43].

5.2 Limitations and Future Work

The main limitation of our study is that we observed participants over a limited time span, about a month. Therefore, our study did not evaluate the *impact* of meeting in virtual environments on scientific discovery. Future research should explore co-designing these systems with scientists to ensure that using the system is motivating, inspires trust, and is reflective of how scientists prefer to do work, followed by longitudinal studies spanning months or years (the typical span of research collaborations), to explore the *actual impact* of novel VR tools. Another limitation is that all participants were using an HMD to meet in VR, however, we recognize that in the future work could also be hybrid [63, 67] with some collaborators collocated and others remote and thus more research is needed to explore how a hybrid format affects the needs of the scientists.

6 CONCLUSION

Our findings provide empirical evidence of *how* scientists utilize shared artifacts, embodied, and spatial interaction in VR for fostering creative scientific discussions. Based on our findings we identified perceived existing affordances of VR meeting applications for supporting remote scientific collaborations and identified areas where additional affordances could prove beneficial. Finally, we offered design requirements for future collaborative VR environments. We expect that these findings will translate well to other scientific domains where researchers collaborate while analyzing vast amounts of data. Remote collaboration is and will continue to be a critical part of scientific collaborations for the foreseeable future, even when occasional face to face meetings occur, due to distance and the involvement of multiple institutions. Therefore, the study and design of future tools for supporting remote data driven scientific discovery continues to be important.

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