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Mixed Reality for Remote Assistance: Effects on Communication
Efficiency and User Experience during Multicommunication

by

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Résumé

L'assistance à distance est devenue de plus en plus importante à mesure que les organisations s'appuient sur la collaboration entre équipes géographiquement dispersées. Les technologies de Réalité Mixte (RM) offrent une solution attrayante pour l'assistance à distance, car elles fournissent des avantages spatiaux et visuels par rapport à la vidéoconférence traditionnelle. Toutefois, on sait encore peu de choses sur la manière dont la RM influence la communication et l'expérience utilisateur dans des conditions réalistes et dynamiques. Les recherches antérieures ont généralement examiné l'assistance à distance dans des environnements hautement contrôlés, négligeant la nature interruptive des situations réelles où les techniciens et les experts doivent souvent diviser leur attention entre plusieurs flux de communication (multicommunication).

Ce mémoire étudie comment la RM affecte l'efficacité de la communication et la convivialité perçue lors de tâches d'assistance à distance dans un contexte de multicommunication (MC). Une expérience en laboratoire contrôlée menée auprès de 72 participants a comparé la RM (HoloLens 2) à la vidéoconférence 2D traditionnelle (iPad Mini), sous conditions MC et sans MC. Des données comportementales quantitatives ainsi que des questionnaires post-tâche ont été analysés.

Les résultats montrent que la RM améliore significativement l'efficacité de la communication, réduisant les demandes d'attente et de répétition, malgré l'absence de différences observées dans la convivialité perçue. À l'inverse, la MC augmente les demandes de répétition, bien que les participants ne rapportent pas une convivialité moindre. Aucune interaction n'a été trouvée entre la RM et la MC, ce qui suggère que les bénéfices de la RM et les défis cognitifs de la MC opèrent de manière indépendante. Dans l'ensemble, les résultats révèlent que les utilisateurs ne perçoivent pas toujours consciemment les différences entre les technologies de communication, alors que leurs comportements divergent de manière significative. Ces observations soulignent la nécessité d'évaluer les outils d'assistance à distance au-delà des seules évaluations subjectives et mettent en lumière l'importance d'une conception centrée sur l'humain en RM.

Mots clés: Réalité Mixte (RM), Assistance à distance, Multicommunication (MC), Efficacité de la communication, Expérience utilisateur (UX), Charge cognitive, Ancrage communicationnel, Richesse des médias, HoloLens 2, Interaction Homme-Machine (IHM)

Méthodes de recherche: Expérience de laboratoire contrôlée, Analyse comportementale quantitative, Observation directe, Questionnaires

Abstract

Remote assistance has become increasingly important as organizations rely on geographically distant collaboration. Mixed Reality (MR) technologies offer an attractive solution for remote assistance as it provides spatial and visual advantages over traditional videoconferencing, yet little is known about how MR influences communication and the user experience in realistic, dynamic conditions. Prior research has typically examined remote assistance in highly controlled settings, overlooking the interruptive nature of real-life scenarios where technicians and experts frequently need to divide their attention across multiple communication streams (Multicommunication). This thesis investigates how MR affect communication efficiency and perceived usability during remote assistance in a multicommunication (MC) context. A controlled laboratory experiment with 72 participants compared MR (HoloLens 2) with traditional 2D videoconferencing (iPad Mini), under MC and no-MC conditions. Quantitative behavioral data and post-task questionnaires were analyzed.

Results show that MR significantly improves communication efficiency, reducing wait requests and repetition requests despite no observed differences in perceived usability. Conversely, MC increases repetition requests, although participants did not report lower usability. No interaction effects were found between MR and MC, suggesting that the benefits of MR and the cognitive challenges of MC operate independently. Overall, the findings reveal that users may not consciously perceive differences between communication technologies, yet their behaviors meaningfully diverge. These insights emphasize the need to evaluate remote-assistance tools beyond subjective ratings and highlight the importance of human-centered MR design.

Keywords: Mixed Reality (MR), Remote Assistance, Multicommunication (MC), Communication Efficiency, User Experience (UX), Cognitive Load, Communication Grounding, Media Richness, HoloLens 2, Human–Computer Interaction (HCI)

Research methods: Controlled laboratory experiment, Quantitative behavioral analysis, Direct observation, Questionnaires

Table of Contents

Résumé.....	2
Abstract	4
Table of Contents	6
List of Tables.....	9
List of Figures	10
Acknowledgments.....	11
Chapter 1: Introduction	12
1.1 Research Question and Approach	14
1.2 Contributions	15
1.3 Next Sections.....	15
Chapter 2: Literature Review	16
2.1 Literature Review Objectives and Approach.....	16
2.2 Remote Assistance.....	17
2.3 MR Technologies.....	18
2.4 Multicommunication	20
2.5 Synthesis and Research Gap.....	21
Chapter 3: Research Model and Hypothesis	23
3.1 Research Model.....	23
3.2 Theories of Communication Grounding, Media Richness, and Cognitive Load	24
3.2.1 Communication Grounding Theory.....	25
3.2.2 Media Richness Theory	25
3.2.3 Cognitive Load Theory.....	26
3.3 MR Technology and Theoretical Foundations	26
3.4 Multicommunication and Theoretical Foundations	28

Chapter 4: Methodology	31
4.1 Experimental Design	31
4.2 Participants	34
4.3 Data Collection and Measurements.....	35
4.3.1 Quantitative data.....	36
4.3.2 Qualitative data.....	36
4.4 Procedure.....	37
4.5 Instruments	40
4.6 Analysis Strategy	41
Chapter 5: Analysis and Results	43
5.1 Descriptive Analysis.....	43
5.1.1 Demographics and Familiarity by Role.....	43
5.1.2 Descriptive Statistics of Perceived Usability	47
5.1.3 Descriptive Statistics of Communication Behaviors.....	48
5.2 Effects of MR on Perceived Usability and Communication Behaviors.....	50
5.2.1 Effects of MR on Perceived Usability (H1)	50
5.2.2 Effects of MR on Communication Behaviors (H2).....	50
5.3 Effects of MC on Perceived Usability and Communication Behaviors.....	51
5.3.1 Effects of MC on Perceived Usability (H3)	51
5.3.2 Effects of MC on Communication Behaviors (H4).....	52
5.4 Moderation Effects of MC on Usability and Behaviors.....	53
5.4.1 Moderation of MC on Perceived Usability (H5).....	53
5.4.2 Moderation of MC on Communication Behaviors (H6)	54
Chapter 6: Discussion	55
6.1 Effects of MR on Perceived Usability and Communication Behaviors.....	55
6.2 Effects of MC on Perceived Usability and Communication Behaviors.....	56
6.3 Interaction Effects Between MR and MC	57
6.4 Contributions	58
6.5 Limitations.....	59

6.6 Future Research	60
6.7 Summary	61
Chapter 7: Conclusion.....	63
Bibliography	65
Appendix.....	72
Appendix A. Main Task Instructions.....	72
Appendix B. System Usability Scale (SUS)	80
Appendix C. Training Task Instructions.....	81

List of Tables

Table 1. Inclusion and Exclusion Criteria	35
Table 2. Demographic Statistics	44
Table 3. Familiarity Statistics by Role	45
Table 4. SUS Scores by MC Condition	47
Table 5. SUS Scores by Communication Technology	47
Table 6. User Behaviors by MC Condition.....	48
Table 7. User Behaviors by Communication Technology	49
Table 8. H1 Significance Assessment	50
Table 9. H2 Significance Assessment	51
Table 10. H3 Significance Assessment	52
Table 11. H4 Significance Assessment	53
Table 12. H5 Significance Assessment	53
Table 13. H6 Significance Assessment	54

List of Figures

Figure 1: Research Model	24
Figure 2. Experimental Protocol	33
Figure 3. Digital Meetings Lab Setting.....	38

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Chapter 1: Introduction

Growing concerns around environmental sustainability, rising travel expenses, geopolitical instability (including war and oil shortages), and the disruptions caused by the COVID-19 pandemic have made remote work not only attractive but, in many cases, indispensable (Chalabi & Dia, 2024; Fidalgo et al., 2023; Tao et al., 2023). Remote assistance is a specific form of remote work where an expert located off-site instructs or supports an on-site, less experienced user in completing a particular task (Fidalgo et al., 2023). Remote assistance plays a crucial role thanks to its relevance in multiple areas, including industrial maintenance (Hebenstreit et al., 2020; Masoni et al., 2017), telemedicine (Anton et al., 2017), and training (Webel et al., 2013).

In industrial environments, manual assembly and the need for effective worker support have gained increasing attention in recent years as production processes continue to grow in complexity (Y. Wang et al., 2017). Videoconferencing is one technology that is used to support workers, particularly during remote assistance. However, it provides limited support for spatial communication and has been shown to be ineffective at conveying essential non-verbal cues that play a critical role in facilitating understanding and maintaining productivity (dos Santos Félix, 2023; Fidalgo et al., 2023; Gurevich et al., 2012; Niedermayr et al., 2022; P. Wang et al., 2021; X. Zhang et al., 2024). Thus, Mixed Reality (MR) technology has gained more attention in recent years, particularly for supporting workers in remote assistance settings (Hebenstreit et al., 2020; J. Zhang et al., 2022). MR is described as the merging of real and virtual world through technology which allows placing virtual objects onto the real world vision (Milgram & Kishino, 1994). Thanks to its immersive qualities, such as 3D annotations, shared gaze, and gestures, it increases spatial clarity and makes remote assistance tasks more efficient by enabling the delivery of real-time, task-specific information directly within the employee's workspace, ensuring that all relevant details appear precisely where they are needed (Fidalgo et al., 2023; Hebenstreit et al., 2020).

Adoption of MR is accelerating rapidly: by 2025, more than 14 million workers in the United States were predicted to use smart glasses in their jobs, representing a significant increase from 400,000 workers in 2016 (Abbas & Jeong, 2024). The combined MR market reached \$72.4 billion

in 2024 and is projected to climb to \$112.0 billion in 2025, with long-term forecasts showing the market reaching \$573.6 billion by 2030 (Pangarkar, 2025). MR is being used in assembly, collaborative workflows, logistics, quality management, and maintenance tasks (Lang et al., 2019). Beyond adoption growth, organizations increasingly rely on MR because it delivers measurable business value. Manufacturers such as Ford Motor Company, for example, use MR applications to integrate and evaluate new vehicle features before a physical prototype is built, enabling managers to assess concepts more rapidly and cost-effectively (Farshid et al., 2018). In addition, DHL reported that the introduction of MR glasses led to a 25% improvement in worker efficiency and a 40% decrease in errors in the warehouses where the technology was deployed (Alumni, 2016).

Although research on MR has expanded rapidly, significant gaps remain in how these systems are evaluated, particularly regarding the role of human factors (Huang et al., 2022). Yan et al. (2023) examine how a novel MR system improves assembly performance, showing gains in efficiency, accuracy, and cognitive effectiveness, while L. Wang et al. (2025) investigate MR-based visual instruction performance, demonstrating reductions in task time, error rates, and execution mistakes across multiple controlled experiments. The evaluation methodologies have mostly utilized objective measurements like task completion times and error rates, which reveal very little of the user's subjective experience. Investigating user experience is important because it captures how individuals perceive and respond to a system, making it a central factor in evaluating and improving technology (Song et al., 2022). Additionally, research shows that studying user experience is essential because it provides a more complete understanding of why technologies succeed or fail (Partala & Saari, 2015).

Most MR evaluations are conducted in highly controlled laboratory settings, where the absence of real-world constraints, interruptions, and variability limits the ecological validity of the findings (Nguyen et al., 2022). In real-world industrial and remote assistance contexts, work is frequently disrupted by interruptions, task switching, and overlapping communication demands. To address this gap, the present study introduces Multicommunication (MC) as an experimental factor, with the goal of better approximating real-world working conditions while preserving the internal validity afforded by laboratory control. MC is defined as “engaging in two or more overlapping conversations”. When people multicomunicate, they engage in multiple conversations at the

same time, dividing cognitive load across threads (Reinsch et al., 2008). However, only a few studies account for the interruptive nature of real life (Abbas & Jeong, 2024; Nguyen et al., 2022). As a result, we know little about how MR affects communication efficiency and user experience when users must divide their attention, manage multiple communication threads, or respond to unexpected messages during task execution. This gap is especially important because MR relies heavily on spatial cues, visual alignment, and shared context, which may be more sensitive to disruptions caused by MC than traditional 2D communication tools.

1.1 Research Question and Approach

Given the lack of research on MR on MC contexts, it becomes necessary to examine how MR functions under the interruptive nature that characterize real-world remote assistance. To address this limitation, the present study investigates the following research question:

RQ: How does MR influence users' perceptions and behaviors during remote assistance tasks, and how does multicomputing influence these effects?

To answer this question, we draw on the theories of communication grounding, media richness, and cognitive load, and employ a controlled experimental approach that manipulates both communication technology and the presence of MC. This approach enables us to systematically assess how MR influences communication efficiency and user experience in scenarios that more accurately reflect the interruptive characteristic of modern industrial communication. Communication grounding theory highlights the coordination efforts required for conversational partners to achieve mutual understanding, making it directly relevant to analyze communication behaviors such as repetition requests, corrections, and clarifications in remote assistance tasks (Clark & Brennan, 1991). Media richness theory posits that different communication media vary in their ability to convey cues and resolve ambiguity (Daft & Lengel, 1986), providing a basis for understanding how MR and 2D technologies may affect differently the efficiency and user experience of the communication technology. Finally, cognitive load theory explains that people have limited mental capacity, and that interruptions or competing tasks can increase mental effort, suggesting users perceive usability and change communication behaviors while multicomputing (Chandler & Sweller, 1991). Together, these theories offer

a set of hypotheses for examining how MR and MC shape both communication behaviors and user experience.

1.2 Contributions

This study contributes to the growing literature on MR and remote assistance by empirically examining how MR performs under interruptive, MC conditions, an aspect largely overlooked in prior research (Nguyen et al., 2022). Although previous studies have applied theories such as communication grounding, media richness, and cognitive load to MR more broadly (Gottsacker et al., 2022; Hou et al., 2025; Thomaschewski et al., 2023), this study specifically extends them to the use of MR for remote assistance while accounting for MC. From a practical standpoint, the findings provide design insights for improving MR remote assistance systems, highlighting opportunities to enhance usability, reduce unnecessary grounding exchanges, and better support users operating in high-demand environments.

1.3 Next Sections

This thesis follows a standard structure. Chapter 2 presents a review of the existing literature on MR, remote assistance, and MC, establishing the theoretical foundation for the study. Chapter 3 introduces the research model and hypotheses, drawing on Communication Grounding, Media Richness, and Cognitive Load theories. Chapter 4 describes the experimental design, procedure, and measurement approach used to investigate the research question. Chapter 5 reports the results of the analysis. Chapter 6 provides the discussion of the findings, including the study's contributions, limitations, and directions for future research. Finally, Chapter 7 concludes the thesis and summarizes its main insights.¹

¹ I declare that I used ChatGPT (Version 5; <https://chat.openai.com/>) between August and December 2025 solely to assist with correcting grammar and improving wording clarity during the thesis writing process. The suggestions provided by the tool were reviewed and selectively adapted to align with my own academic writing style and intent.

Chapter 2: Literature Review

This chapter reviews the key bodies of literature that inform this thesis. It examines prior work on remote assistance, the technological developments that enable it, and the evolution of communication tools used in geographically distributed collaboration. It then MR technologies and their growing role in improving communication efficiency in remote assistance settings. Finally, it reviews the concept of MC, highlighting how the interruptive nature of real-world work environments may influence collaborative performance. Together, these streams of literature help establish the theoretical context for this study and identify the gaps that motivate the research model and hypotheses developed in Chapter 3.

2.1 Literature Review Objectives and Approach

The objective of this literature review is to build a comprehensive understanding of the three main domains that unite this thesis: remote assistance, MR technologies, and MC. First, it seeks to define and contextualize remote assistance, including its main advantages and limitations as compared to face-to-face interaction. Second, it explores MR and how MR technologies are being adopted to address communication challenges in remote assistance. Finally, to inform the other element of our research question, it examines the concept of MC, clarifying its distinction from related constructs such as multitasking, while identifying the current research gap regarding its influence on MR remote assistance collaboration.

The methodology for this review used a structured search strategy across two primary academic databases: Google Scholar and Web of Science. Searches combined the keywords and synonyms listed in the concept matrix, organized into three thematic categories: (1) Remote Assistance (remote assistance, remote maintenance, remote collaboration, remote guidance, remote instructions, remote training, distant teamwork); (2) Mixed Reality (mixed reality, augmented reality, virtual reality, extended reality, digital twin); and (3) Multicommunication (multicommunication, multitasking, dual task, task switching, interruptions, dual attention, multifocal attention). Boolean operators (AND, OR) were applied to combine terms across categories to retrieve a broader range of relevant studies. Inclusion criteria focused on peer-reviewed sources, such as journal articles, with priority given to recent research published in the last ten years (2015-2025). A ten-year window was chosen because MR technologies have only

become widely accessible and applied in industrial and collaborative contexts within this period, with rapid advances in hardware and software making older studies less comparable to current practice (Hebenstreit et al., 2020; X. Zhang et al., 2024). This approach ensured that the review integrates both foundational definitions and the most current empirical evidence to inform the thesis framework and identify potential research gaps.

2.2 Remote Assistance

Remote assistance is a task-focused interaction in which a remote helper (herein termed the expert) guides and assists an untrained user (herein termed the technician) on how to complete a physical task with a given object (Gurevich et al., 2012; Rasmussen et al., 2022). Typically, this collaboration happens synchronously, where the expert is not physically located in the same space as the physical object (Fidalgo et al., 2023). Examples of remote assistance include a customer calling a call center to figure out how to fix a printer or an onsite doctor receiving instructions from a offsite medical expert on conducting a complex medical procedure (Gurevich et al., 2012).

Remote assistance provides several advantages over in-person assistance as the latter is not always viable. The expert may be unavailable, required at a distant site, or in demand at multiple locations at the same time. In such circumstances, remote assistance may be the only feasible approach. Even when alternatives exist, it can yield substantial time and cost savings, making it an attractive choice (dos Santos Félix, 2023; L. Wang et al., 2025). In a traditional remote assistance scenario, the technician may use a standard video communication device, such as Zoom, to transmit the information to the expert. However, some of the information could be lost as it is limited to the technician's point of view and research has found it may be inefficient for maintenance tasks (dos Santos Félix, 2023; Niedermayr et al., 2022; Rasmussen et al., 2022). In remote collaboration on industrial tasks, clear and detailed remote expert instructions are key to efficient task performance and a shared visual representation of the technician's workspace is useful for supporting those tasks (Gurevich et al., 2012; X. Zhang et al., 2024). In the case of video and audio calls, this visual representation lacks in-depth spatial communication and is reported as ineffective for non-verbal cues, such as gestures and gaze, which is important for increasing productivity (dos Santos Félix, 2023; Niedermayr et al., 2022).

Remote assistance needs to address two key challenges: first, remote users require a virtual representation of the local user's space to understand all necessary details to provide the right

instructions. Second, the communication needs to be efficient between both parties (Fidalgo et al., 2023; L. Wang et al., 2025). Collaborating efficiently using 2D displays like computers, smartphones, and tablets is difficult because many tasks need shared understanding and situational awareness in a complex 3D environment (Fidalgo et al., 2023; Yan et al., 2023). Additionally, there are two additional challenges for communicating with 2D devices: first, the field of view (FOV) from the expert is limited and depends on the technician; second, the technician must hold the device for showing the expert, limiting their range of movement (Niedermayr et al., 2022). Furthermore, expert's instructions are often hard to follow, especially when explaining assembly positions or attributes. Technicians may forget the steps, so experts must repeat their explanations or use gestures several times before the task is understood. In summary, 2D communication channels such as video-based remote assistance makes collaboration at a distance possible, but it struggles to deliver the spatial and non-verbal cues needed for efficient communication during complex tasks (Yan et al., 2023).

2.3 MR Technologies

The immersive qualities of MR technology can help overcome these challenges of 2D displays. According to Speicher et al. (2019), there is no consensus on a definition for MR technology, but the most popular understanding among researchers is based on the Reality-Virtuality Continuum, originally articulated by Milgram & Kishino (1994). In this continuum there are two extremes: a fully real and a fully virtual environment. MR is described as everything in between those extremes, not including the extremes. AR is described as the combination of real and virtual objects in a real environment, running interactively and in real time, aligning real and virtual objects with each other (Azuma et al., 2001). For example, IKEA Place is an AR app where users can see virtual 3D furniture in a real environment. On the other hand, VR is described as a “fully virtual view” by multiple authors and it is defined as a computer-generated display that allows users to have a sense they are present in a completely different environment and be able to interact with it (Schroeder, 1996). Therefore, we could tell that following this definitions AR is included in the MR scope and there is still a debate between researchers on whether to include or not VR as part of MR.

There are multiple authors claiming the use of MR for remote assistance is superior to traditional 2D video-based calls. MR technology enables a more intuitive and immersive collaborative experience than videoconferencing (Bai et al., 2020). MR devices create a shared visual space by

enabling the remote expert to view the local technician's perspective, while supporting both verbal and non-verbal cues to facilitate effective task guidance (Torrence et al., 2023). MR remote collaboration research supports expert instruction in two complementary ways. First, the sharing of the technician's workspace so remote experts can explore, maintaining workspace awareness and precise spatial reference. Second, the MR interface adds non-verbal cues directly in the worker's environment, such as annotations (text, pointers, sketches), hand gestures, gaze indicators, and 3D models, to clarify intent and improve the effectiveness of guidance (X. Zhang et al., 2024). Numerous authors also described the benefits of MR technologies for remote assistance collaboration are the sharing of non-verbal cues, such as eye gaze and gestures; annotations; user-friendly interfaces and shared field of view of the technician's workspace (Torrence et al., 2023). The sharing of gestures, gaze, annotations and other non-verbal cues, which are lost during videoconferencing, can significantly result in a better user experience and improved task performance (Yan et al., 2023). These qualities are particularly important for maintenance tasks where non-verbal communication is key for complementing the expert's instructions (Torrence et al., 2023).

The main advantage of MR over traditional assembly instructions is their ability to deliver real-time, context-specific information directly within the technician's workspace. This integration allows the technician to view all relevant details precisely at the correct location on the workplace (Hebenstreit et al., 2020; Masoni et al., 2017). This capability is further enhanced by studies which show that using non-verbal cues like pointers, arrows, gestures, eye gaze, and virtual avatars can effectively transfer expert knowledge to technicians. These cues significantly boost collaboration efficiency, awareness, user attention, and the overall user experience in MR remote assistance environments (Yan et al., 2023).

While MR provides a clear advantage over traditional methods, current systems face two primary limitations. First, the shared 3D stereoscopic scenes often struggle to balance high quality with real-time updates, making it difficult for experts to accurately understand the technician's workspace and precisely place virtual instructions. This can lead to virtual objects having incorrect spatial relationships with the physical environment, causing confusion for technicians. Second, experts face a heavy workload when creating instructions for complex industrial processes. They must generate multiple detailed instructions for each step, which not only is time-consuming but

also results in non-standardized guidance influenced by personal preferences from the expert (X. Zhang et al., 2024). In summary, MR technologies clearly enhance remote assistance by enriching communication with annotations, gaze, and shared spatial context, reducing many of the inefficiencies of 2D video calls. However, there are some limitations, such as incorrect spatial relationships and heavy workload, that needs to be addressed.

2.4 Multicommunication

A second key element of our research focuses on MC. The phenomenon of MC was first introduced by Reinsch et al. (2008) and it they defined it as “engaging in two or more overlapping conversations”. Cameron and Webster (2011) expanded the definition by including any communication task with interleaved turns, where the focal communicator switches back and forth between different communication threads. In MC, the main actors include the focal communicator engaged in primary communication, their immediate communication partners involved in secondary tasks, and broader external stakeholders who may be indirectly affected by or involved in the communication processes. MC share some similarities with multitasking, phubbing and many other phenomena involving simultaneous management of multiple tasks. When people multitask, they engage in multiple tasks at the same time to achieve an overall goal, allocating cognitive resources across the tasks (Abbas & Jeong, 2024). Therefore, MC is within the umbrella of multitasking as it is juggling between multiple conversations. However, not all multitasking counts as MC if they do not include communication with other people nor IT use. For instance, browsing the web while listening to music could be considered multitasking, while instant messaging while on a remote meeting could be considered both multitasking and MC (Jiang et al., 2023).

Multicommunication has several impacts, both at the individual and group level. At the individual level, studies have shown that MC can negatively affect task performance, engagement and cause lower rates of problem-solving in work settings. It can also cause lack of self-regulation during work and reduce contributions in meetings. However, MC also has potential benefits, such as informational gains through secondary conversations. At the group level, MC influences social evaluations, often perceived negatively in business contexts, affecting perceptions of civility, professionalism, and competence. Additionally, it can cause communication errors within groups and negatively impact relationship quality, task experience and satisfaction (Jiang et al., 2023).

While MC may have multiple effects on the individual and group level, there are various factors that influence those impacts. At the individual level, studies show that when two communication tasks are unrelated (off-task MC) there can be negative outcomes such as reduced performance and attention loss. When the two communication tasks are related, MC may be productive by providing additional informational gains (e.g., texting a colleague to gather information needed for a meeting you are currently attending). MC frequency and timing also play a role, with short interval interruptions having stronger negative effects on task performance than long intervals. At the group level, MC media choice further shapes outcomes, as combinations like instant messaging plus voice have been shown to generate worse partner evaluations compared to text-only exchanges. Additionally, whether the MC is self- or other-initiated, the multicomunicator's gender and the social expectations within an environment also shape how MC is judged or perceived (Jiang et al., 2023).

Although the broader topic of multitasking in remote collaboration has been a subject of study, there is a critical research gap for the specific case of MC during MR remote assistance. As AR and VR technology evolves and new MR collaborative apps are being launched, research on multitasking in MR environments is becoming increasingly important (Abbas & Jeong, 2023; Nguyen et al., 2022). Recognizing the increasing importance of multitasking, researchers are exploring new approaches to enhance this skill. MR technology, which seamlessly integrate physical and digital realities, offer a promising platform for multitasking. MR enables more user interaction than other technologies and MR with head-mounted displays let the user work with their hands free (Abbas & Jeong, 2023; Hebenstreit et al., 2020). Additionally, current research on MC has primarily focused on conventional communication channels, such as instant messaging platforms and social media apps (Jiang et al., 2023). As a result, there is a notable gap in understanding how MC influences emerging technologies, such as MR technologies. Therefore, a comprehensive understanding of how these technologies affect MC outcomes is still lacking.

2.5 Synthesis and Research Gap

In summary, the reviewed literature provides insights into our current understanding of remote assistance, MR technologies, and MC. Remote assistance offers clear advantages for efficiency, cost reduction, and accessibility but struggles with limitations in spatial awareness, non-verbal cue transmission, and communication efficiency when using 2D devices. MR technologies have

emerged as a potential solution, enriching collaboration with shared space visualization, annotations, gaze indicators, and 3D content, improving task performance, communication efficiency and user experience. At the same time, the phenomenon of MC adds another layer of complexity, as individuals increasingly manage overlapping communication threads during remote collaboration. While MC has been shown to generate both positive and negative outcomes depending on task relevance, frequency, and context, its effects on MR remote assistance remain understudied.

Taken together, the literature suggests that while MR can overcome many of the limitations of traditional remote assistance, its adoption may not eliminate the cognitive and communicative challenges associated with MC. The immersive features of MR may reduce misunderstandings and strengthen collaboration, but interruptions and secondary communication threads can still disrupt task performance and communication, shaping the experience differently. Therefore, it is an excellent opportunity to study the effect of this technology on user experience and discover how it shapes user behaviors.

Despite advances in remote assistance, MR technologies, and MC studies, there remains a critical research gap involving their intersection. Most studies on MR remote assistance are made in controlled settings, where the interruptive nature of real-world situations is absent. Users are prone to interruptions on a daily basis while they work. In addition, MC research has largely examined conventional settings such as business meetings or classrooms, without exploring immersive MR environments. Therefore, little is known about how MC manifests in MR remote assistance settings. Addressing this gap is crucial, as the use MR technologies is increasing throughout the years (Abbas & Jeong, 2024). This underscores the urgency of investigating how MC affect collaboration and user experience in MR remote assistance. Bridging these areas of research together can give us a better understanding of the challenges people face when multicommuting in immersive technologies and help design MR systems that are more effective and easier to use.

Chapter 3: Research Model and Hypothesis

To examine how different communication technologies and MC influence users' communication efficiency and perceptions in a remote assistance context, this study developed the research model. The framework proposes that both MR and MC shape communication efficiency and user experience by affecting the process losses (observable communication behaviors) and the perceived usability of the communication technology. Accordingly, the following research question is proposed:

RQ. How does MR influence users' perceptions and behaviors during remote assistance tasks and how does multi-communicating influence these effects?

3.1 Research Model

The research model is developed based on prior studies in MR and MC, as well as existing theoretical foundations. Building on the theory of communication grounding, media richness theory, and cognitive load theory, the model examines how the communication channel (MR vs. videoconferencing) and the presence of MC influence communication efficiency and perceived usability in remote assistance tasks. Addressing the research questions, six main hypotheses are proposed. For the effects of communication channel, hypotheses are grounded in communication grounding and media richness theories, which suggest that richer visual cues provided by MR technologies, such as gestures, gaze, and annotations, enhance mutual understanding and reduce communication friction. For the effects of MC, hypotheses are based on cognitive load theory and existing research on MC, suggesting that managing multiple communication threads simultaneously increases mental workload and may decrease perceived usability. Additionally, the model also posits an interaction between MC and the communication channel because as MR affords richer, spatially visual cues, it could reduce communication issues and improve usability relative to videoconferencing. However, these advantages may be attenuated when users are multicommuting, as divided attention elevates cognitive load.

Consequently, the model (Figure 1) includes two independent variables (communication channel and MC) and two dependent constructs (communication behaviors and perceived usability), as

well as moderation paths from MC on the relationship between the communication channel and each outcome.

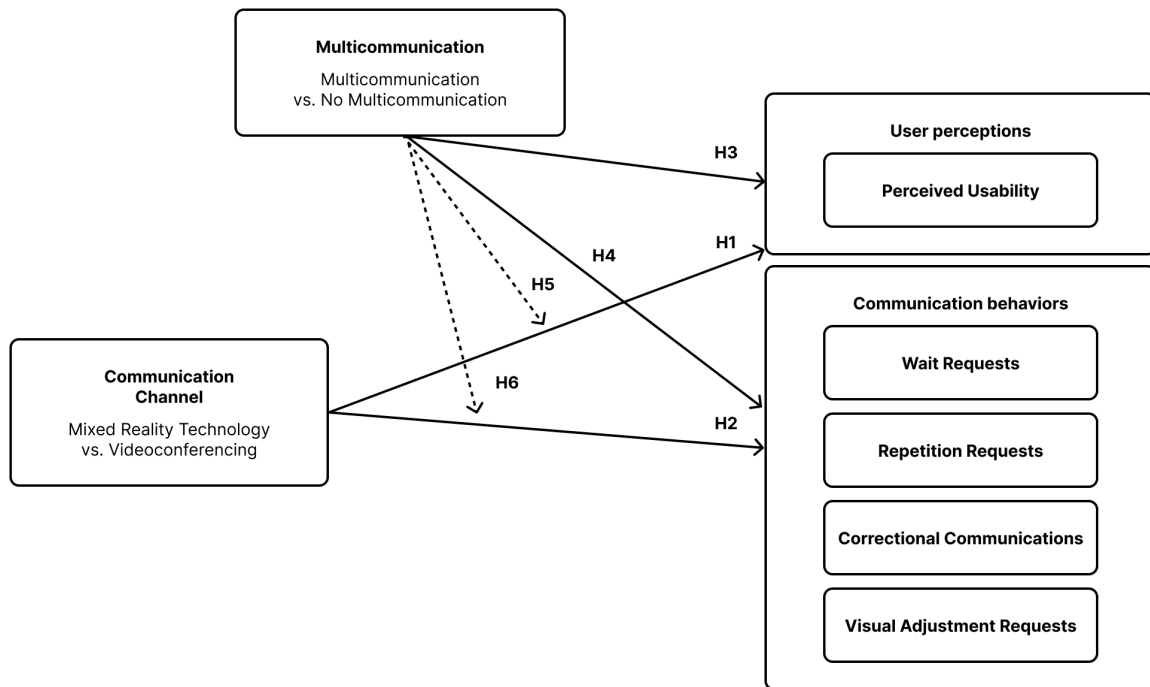


Figure 1: Research Model

3.2 Theories of Communication Grounding, Media Richness, and Cognitive Load

As illustrated earlier, this study draws on three theoretical foundations for hypothesis development: the theory of communication grounding, media richness theory, and cognitive load theory. Together, these theories explain how communication technologies and MC conditions may influence both the behavioral and perceptual dimensions of a user in a remote assistance setting. This section presents the theoretical bases supporting the formulation of the research model and hypotheses.

3.2.1 Communication Grounding Theory

The theory of communication grounding provides a framework for understanding how collaborators establish mutual understanding or “common ground” through communication. In remote assistance, where an expert and technician are physically separated, establishing common ground becomes more challenging due to the absence of shared physical context. Grounding involves two phases: a presentation phase, during which a speaker produces evidence through gestures or visual cues, and an acceptance phase, during which the partner acknowledges or confirms understanding through verbal or non-verbal signals (Brennan, 1991).

Remote assistance scenarios incur several grounding costs, such as formulation, production, reception, understanding and repair costs (Clark & Brennan, 1991). For example, a technician interpreting an expert’s spoken instruction through a 2D video stream may face higher reception and display costs compared to using a MR headset that provides spatial annotations and gestures. Similarly, repair costs arise when communication requires repetition or correction, such as when a technician performs an incorrect adjustment and must redo the task.

The principle of least collaborative effort suggests that communicators minimize effort by relying on richer, more immediate feedback cues (Clark & Wilkes-Gibbs, 1986). Consequently, MR tools that support gaze, gesture, and spatial annotation can reduce grounding costs by enabling faster mutual understanding, while videoconferencing, which lacks depth and spatial reference, may increase such costs.

3.2.2 Media Richness Theory

Media richness theory complements communication grounding by emphasizing that communication effectiveness depends on the channels’ capacity to convey multiple cues and immediate feedback (Daft & Lengel, 1986). Richer media, those that allow visual, verbal, and non-verbal exchange, are better suited for tasks involving ambiguity and interdependence. MR technology, for instance, provides high media richness through its unique features, such as 3D spatial cues, gestures and real-time annotations. This richness helps collaborators interpret complex maintenance instructions more intuitively, thus it may improve perceived usability and communication efficiency.

In contrast, videoconferencing offers more limited cue variety and restricted spatial awareness, making it less effective for highly collaborative physical tasks. The theory suggests that when the communication medium matches the task's level of ambiguity, communication efficiency increase (Daft & Lengel, 1986). Therefore, in remote assistance contexts, MR's higher richness is expected to bring smoother collaboration and enhance users' perceptions of usability compared to videoconferencing.

3.2.3 Cognitive Load Theory

Cognitive load theory provides a complementary perspective by explaining how MC may affect user performance and perceptions. According to this theory, human working memory has limited capacity, and performance deteriorates when cognitive demands exceed available mental resources (Sweller, 1988). Cognitive load is categorized into three types: intrinsic, extraneous, and germane load. Intrinsic load relates to the inherent complexity of the task or information itself. Extraneous load results from unnecessary cognitive effort caused by suboptimal design, such as poor interface layout, unclear instructions, or fragmented visual information. Germane load, on the other hand, refers to the mental effort devoted to learning, reasoning, and integrating new knowledge (Chandler & Sweller, 1991). When extraneous load is minimized and cognitive resources are focused on germane processing, communication efficiency improve.

In remote assistance, MR interfaces may both mitigate and amplify cognitive load depending on task design. On one hand, MR's spatial anchoring and visual feedback may reduce the mental effort required to interpret complex instructions. On the other hand, when MC is introduced, the same immersive environment may overload users, undermining its usability benefits.

3.3 MR Technology and Theoretical Foundations

The first two hypotheses of this study are grounded in the theory of communication grounding and media richness theory, which together provide a framework for explaining how the communication channel (MR vs. Videoconferencing) affects both user communication behaviors and perceptions during remote assistance. We propose that these effects can be explained through the mechanisms of communication grounding and media richness: MR's immersive environment offers spatial, visual, and gestural cues that can reduce communication breakdowns and increase the perceived usability of the technology. Studies suggests that integrated communication cues within MR

devices, such as visual gestures, gaze cues, and virtual representations, significantly enhance perceived usability and collaboration efficiency by supporting richer, more natural interactions between geographically distributed users (Huang et al., 2022; L. Wang et al., 2025; X. Zhang et al., 2024)

In remote assistance contexts, different communication tools vary in how effectively they support grounding behaviors and the richness of information exchange. According to the theory of communication grounding, successful collaboration depends on establishing common ground through shared cues and immediate feedback (Clark & Brennan, 1991). MR technologies replicate face-to-face communication more closely than videoconferencing by allowing the exchange of both verbal and non-verbal cues, such as gestures, gaze direction, and spatial annotations. These affordances can reduce grounding costs, including formulation and repair efforts, by making instructions clearer and more intuitive for technicians. Consequently, the use of MR technology is expected to result in fewer inefficient communication behaviors, such as repetition requests or correctional communications, compared to traditional 2D videoconferencing.

In this study, inefficient communication behaviors are conceptualized as communication costs incurred during the process of grounding (Clark & Brennan, 1991). These costs represent the additional effort required by collaborators to achieve mutual understanding. Four specific types of communication costs are proposed in this study based on systematic observation of recurrent communication breakdowns observed during MR-mediated remote assistance tasks.:

- Wait requests: which occur when one participant pauses to ask for clarification or confirmation before continuing the task
- Repetition requests: which happen when a participant asks the other to repeat the instruction
- Correctional communications: which involve explicit verbal efforts to correct an error or misinterpretation
- Requests for adjusting the field of view (FOV): which occur when the visual perspective needs to be realigned to ensure shared visibility of the workspace.

In addition, Media Richness Theory posits that communication media differ in their ability to convey multiple cues, provide immediate feedback, and establish shared understanding (Daft &

Lengel, 1986). Richer media are better suited for tasks characterized by high ambiguity and interdependence, as they allow collaborators to process information more quickly and effectively. MR, as a high-richness medium, supports multimodal communication by integrating gestures, gaze tracking, 3D annotations, and real-time spatial context. These features enhance situational awareness and co-presence, allowing experts and technicians to synchronize actions with minimal verbal clarification. Videoconferencing, in contrast, is a leaner medium that restricts the transmission of non-verbal information, which can reduce communication efficiency and user experience.

Therefore, MR's combination of grounding and richness is expected to improve the collaborative process by reducing communication costs and enhancing user experience. Users are likely to perceive MR as a more usable and supportive communication tool while also exhibiting fewer communication inefficiencies during remote assistance sessions.

- H1: The use of Mixed Reality technology during remote assistance will result in higher perceived usability compared to videoconferencing.
- H2: The use of Mixed Reality technology during remote assistance may decrease inefficient communication behaviors compared to videoconferencing.
 - H2a: The use of Mixed Reality technology during remote assistance will decrease wait requests compared to videoconferencing.
 - H2b: The use of Mixed Reality technology during remote assistance will decrease repetition requests compared to videoconferencing.
 - H2c: The use of Mixed Reality technology during remote assistance will decrease correctional communications compared to videoconferencing.
 - H2d: The use of Mixed Reality technology during remote assistance will decrease requests for adjusting the field of view (FOV) compared to videoconferencing.

3.4 Multicommunication and Theoretical Foundations

The next set of hypotheses in this study are grounded in the Cognitive Load Theory and prior research on multitasking (Sweller, 1988). This theory provides a framework for explaining how multicommunicating affects user perception and communication performance in remote assistance contexts. We propose that these effects can be explained through the mechanisms of cognitive

overload and divided attention, which may increase grounding costs, reduce perceived usability, and generate process losses during task execution.

In remote assistance, experts and technicians may need to interact through a primary communication channel while also managing secondary tasks such as responding messages or communicating with other colleagues. This multicommuting condition, divides users' cognitive resources between multiple communication threads. According to Cognitive Load Theory, human working memory is limited, and performance deteriorates when mental demands exceed available capacity. When attention is divided across tasks, intrinsic and extraneous cognitive load increase, which can interfere with users' ability to process information efficiently and maintain communication clarity (Chandler & Sweller, 1991; Sweller, 1988).

Empirical research has supported these predictions. Abbas and Jeong (2024) found that multitasking in MR environments significantly increased mental workload and task prioritization difficulty, while Nguyen et al. (2022) observed that interruptions during MR collaboration created unnatural delays and reduced task efficiency. These findings suggest that handling concurrent communication threads increases mental demand and may lead users to perceive the technology as less usable, as they experience overload and distraction during interaction.

- H3: Multicommuting will negatively affect perceived usability during remote assistance.

In addition to affecting user perception, MC may also increase process losses, or observable inefficiencies in communication behavior. Process losses occur when individuals are unable to manage multiple communication threads effectively, resulting in interruptions, confusion, or breakdowns in mutual understanding (Cameron & Webster, 2011a). In a remote assistance context, experts and technicians engaging in MC may experience greater mental workload and attentional switching costs. The increased cognitive effort required to manage simultaneous communication flows may manifest as more repetition and wait requests, as well as more frequent correctional communications and visual adjustment requests.

- H4: Multicommuting will increase process losses during remote assistance.
 - H4a: Multicommuting will increase wait requests during remote assistance.

- H4b: Multicommunication will increase repetition requests during remote assistance.
- H4c: Multicommunication will increase correctional communications during remote assistance.
- H4d: Multicommunication will increase requests for adjusting the field of view (FOV) during remote assistance.

Finally, it is expected that MC will interact with the effects of the communication channel (MR vs. videoconferencing) on both usability and communication efficiency. While MR technology enhances usability and reduces grounding costs by providing richer cues, users may experience cognitive overload, as they must simultaneously manage multiple communication streams while interacting in an already complex environment. As a result, the usability and efficiency advantages of MR may diminish under MC conditions. Therefore, MC is expected to moderate the relationships between communication technology, perceived usability, and communication behaviors.

- H5: Multicommunication will moderate the effect of communication technology on perceived usability.
- H6: Multicommunication will moderate the effect of communication technology on process losses.
 - H6a: Multicommunication will moderate the effect of communication technology on wait requests.
 - H6b: Multicommunication will moderate the effect of communication technology on repetition requests.
 - H6c: Multicommunication will moderate the effect of communication technology on correctional communications.
 - H6d: Multicommunication will moderate the effect of communication technology on requests for adjusting the field of view (FOV).

Chapter 4: Methodology

This chapter describes the methodological approach used to investigate how MR and MC influence communication efficiency and user experience during remote assistance. To address the research question and test the hypotheses, a controlled laboratory experiment was designed to isolate the effects of communication technology and MC demands under standardized conditions. The chapter outlines the experimental design, participant recruitment, measurements, procedures, instruments and analysis strategy employed in this study. By integrating both objective behavioral indicators and subjective self-reported measures, the methodology ensures a comprehensive understanding of how MR and MC influence communication behaviors and user perceptions during collaborative technical tasks. The following sections detail each component of the research protocol and describe how data was collected and analyzed.

4.1 Experimental Design

A controlled laboratory experiment was conducted at the Digital Meetings Laboratory at HEC Montréal to examine how communication technology (MR vs. videoconferencing) and MC influence user experience and communication behaviors during remote assistance. An experimental approach was chosen because it enables systematic manipulation and control of independent variables. In this case, communication technology and MC conditions while keeping all other factors constant. This level of control would not be achievable through surveys or interviews, which rely on self-reported perceptions rather than directly observable performance.

Although laboratory experiments are sometimes criticized for limited ecological validity, this study attempted to improve one aspect of ecological validity by explicitly incorporating MC as an experimental factor. MC was introduced to reflect the interruptive and multitasking nature of real-world industrial and remote assistance contexts, where users frequently manage overlapping communication demands. By systematically integrating MC within a controlled laboratory setting, the study increases ecological realism while maintaining experimental control, allowing real-world communication complexity to be examined without compromising internal validity.

The use of a laboratory experiment allows for causal inference, providing stronger evidence of how MR and MC directly affect communication efficiency and user experience. It also permits the

collection of both objective behavioral data and subjective perceptual measures under standardized conditions, ensuring reliability and replicability.

A 2×2 between-subjects design was adopted, comprising four experimental conditions: MR-MC, MR-no-MC, Videoconferencing-MC, and Videoconferencing-no-MC (see **Figure 2**). Participants were randomly assigned to one of these four conditions to ensure an equal distribution across all combinations and minimize selection bias. The order of experimental sessions was randomized and counterbalanced, ensuring that all conditions were represented evenly throughout the data collection period.

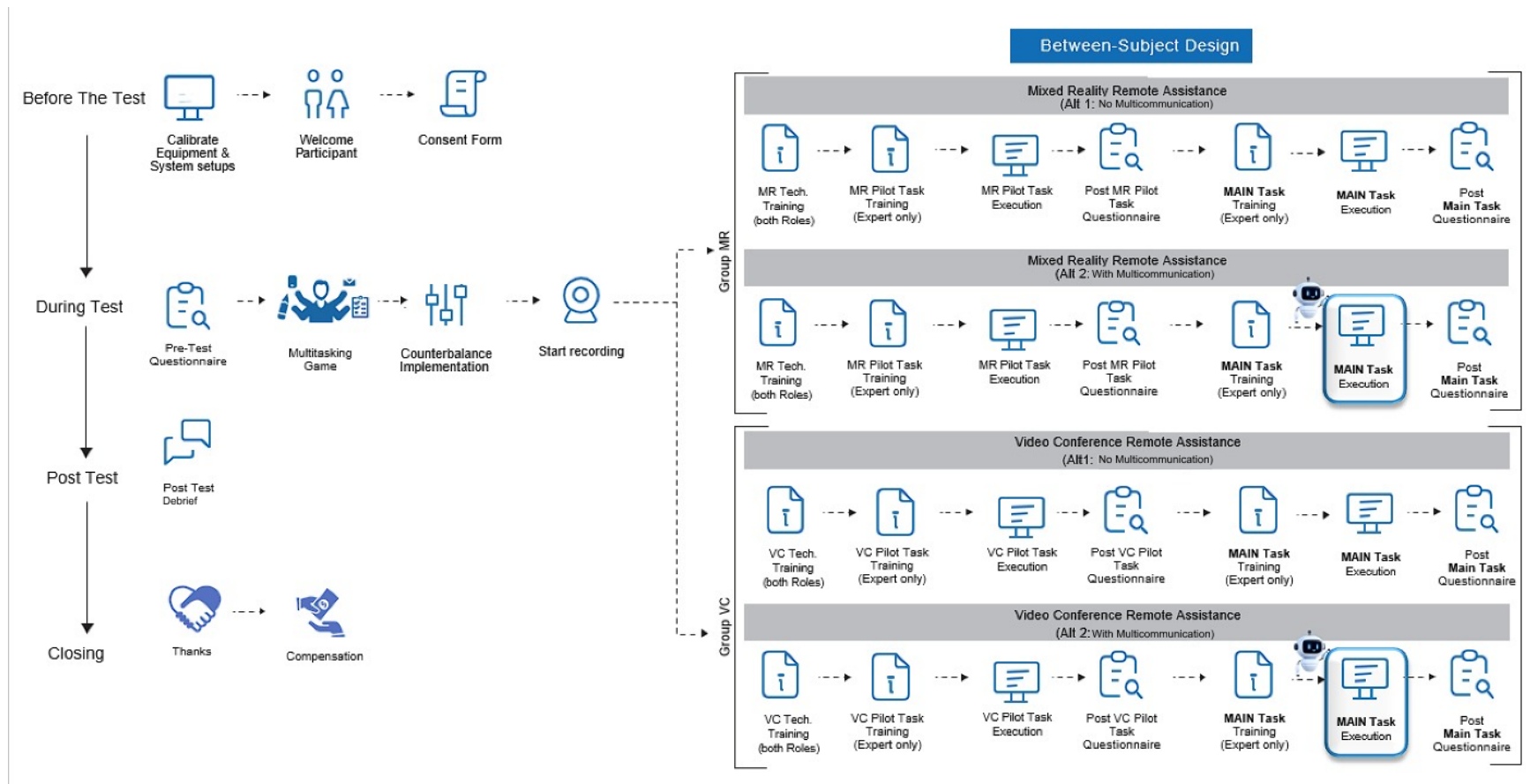


Figure 2. Experimental Protocol

Each session consisted of a pair of participants, one assigned the role of expert and the other as technician, who remained in their designated roles throughout the experiment. The expert received additional training prior to the remote assistance session to ensure a higher level of task knowledge and familiarity with the procedure. During the session, the expert provided remote guidance using the assigned communication technology, while the technician executed the task in a different room.

The task simulated a remote assistance scenario commonly found in industrial maintenance and training contexts (see **Appendix A**). The technician was required to set up and operate a 3D printer (Crealty Ender 3 V3 SE) following real-time instructions from the expert located in a separate room. The MR condition utilized the Microsoft HoloLens 2, allowing holographic annotations and spatial cues to support communication, whereas the 2D condition used videoconferencing via iPad Mini. In the MC conditions, technicians additionally received automated secondary communications through an iPhone 16 Pro, simulating MC scenarios that required divided attention.

All sessions were conducted under the same controlled environmental conditions to ensure consistency across trials. The use of a laboratory setting minimized external interference, ensuring that any observed differences could be attributed to the effects of MR and MC rather than uncontrolled contextual factors.

4.2 Participants

Participant recruitment was conducted through HEC Montréal's Panelfox screening platform. This platform provides access to a diverse participant pool, ensuring broad demographic and background representation and thus a more generalizable source of participants. Invitation emails were distributed via the platform to registered users. The email described the study's objectives, gave a concise overview of the experimental procedure, indicated an approximate duration of 1.5 hours, and specified the type of compensation offered. It also detailed the inclusion and exclusion criteria, as shown in **Table 1**.

Individuals interested in participating were first required to complete a screening questionnaire to verify that they met the inclusion criteria. Those who qualified were then provided with a list of available time slots from which they could select their preferred session.

In total, 40 experimental sessions were conducted, involving 80 participants. However, four sessions were discarded due to technical issues such as repeated internet connection losses or a power outage on campus. To maintain data quality and ensure the validity of the results, the datasets from these sessions were excluded from the analysis. Consequently, the final dataset comprised 36 sessions with 72 valid participants whose data met the experimental criteria.

Table 1. Inclusion and Exclusion Criteria

Inclusion criteria	Exclusion criteria
Participants had to be 18 years of age or older.	Individuals with visual impairments not corrected by glasses.
They needed sufficient oral and written English proficiency to read study materials and communicate effectively with other participants during group tasks.	Individuals suffering from motion sickness.
	Individuals with pacemakers or implanted medical devices.
	Individuals prone to migraines, balance disorders, or epilepsy.

4.3 Data Collection and Measurements

This section describes the measurements and procedures used to collect data throughout the experiment. Because user communication and experience may be directly influenced by the type of remote assistance technology employed, it was essential to collect both quantitative and qualitative data to gain a comprehensive understanding of participant behaviors and perceptions. The collected data reflect how experts and technicians interacted with each communication technology (MR vs. Videoconferencing) and how these technologies, with or without MC, affected perceived usability and communication behaviors.

4.3.1 Quantitative data

Quantitative data were collected through a series of self-administered questionnaires designed to capture participants' demographic characteristics, familiarity with technology, and perceptions of usability.

Demographics and Familiarity with MR: Before starting the experimental tasks, participants completed a demographic questionnaire that gathered information on specific age, gender and education level. Additionally, participants reported their familiarity MR headsets, experience using MR applications, and experience operating 3D printers. These variables helped control participants' usability perceptions according to their prior experience.

System Usability Scale (SUS): After completing each experimental condition, participants evaluated the usability of the communication technology used during the session by completing the System Usability Scale (SUS) (Brooke, 2013). The SUS consists of ten standardized statements rated on a 5-point Likert scale, ranging from “strongly disagree” to “strongly agree” (see **Appendix B**) This instrument was employed to capture participants' subjective perceptions of usability, including ease of use, consistency, and confidence when using the technology. The resulting SUS scores provided a quantitative measure of perceived usability for each communication condition (MR, videoconferencing, and with or without MC), allowing for direct comparison across conditions. The SUS item phrasing was adapted to the context of this study, replacing the word ‘system’ with ‘technology’ to better reflect the nature of the communication tools evaluated and ensure conceptual clarity for participants.

4.3.2 Qualitative data

During all experimental tasks, participants' interactions were recorded using synchronized video and audio capture cameras to allow detailed behavioral analysis. These recordings enabled the observation of real-time communication exchanges between the expert and the technician under each experimental condition. The recordings were later reviewed using The Observer XT software to systematically identify and code specific communication behaviors. The following communication behaviors were coded to assess process losses that may occur when participants engage in remote assistance tasks involving MC. Process losses are conceptualized as communicative inefficiencies that emerge when an individual's attention is divided across multiple communication channels or when information flow is disrupted (Cameron & Webster, 2011).

These behaviors represent observable manifestations of diminished multicommuting performance, including corrective instructions, visual adjustments requests and wait and repetition requests.

- **Wait request:** A wait request occurs when one participant asks the other to pause the communication. Each time a participant explicitly requested a pause or delay to process information, the instance was coded as a wait request.
- **Repetition request:** Repetition requests refer to instances when a technician explicitly asks the expert for an instruction or statement to be repeated. These reflect information-processing process losses, where communication clarity or message encoding is compromised because of divided attention or interference from concurrent communication (Cameron & Webster, 2011b). Every instance the technician requested for a repetition was captured as an event.
- **Correctional communications:** In this experiment, corrective instruction refers to instances in which the expert provides verbal corrections to guide the technician's actions during the task. These behaviors reflect moments when shared understanding temporarily breaks down and must be restored through additional communicative effort (Cameron & Webster, 2011b). We recorded an event each time the expert intervened to correct or redirect the technician's actions to realign task progress.
- **Visual adjustment request:** Visual adjustment requests refer to moments when the expert explicitly asks the technician to change the camera view or adjust the field of vision to clarify the shared workspace. Each visual adjustment request was counted when an expert requested the technician to modify the viewpoint to improve visibility or alignment.

4.4 Procedure

Participants were instructed to arrive at the Digital Meetings Laboratory at HEC Montréal. Upon arrival, they were welcomed and randomly assigned to one of two rooms, which determined their experimental role: expert or technician. The technician was positioned in Room 1, while the expert was assigned to Room 2. Both rooms were soundproof to ensure clear communication only through

the assigned technology. The setting of the laboratory is shown in **Figure 2**. Before beginning the session, participants were invited to leave their personal belongings in a designated area and silence their mobile devices.

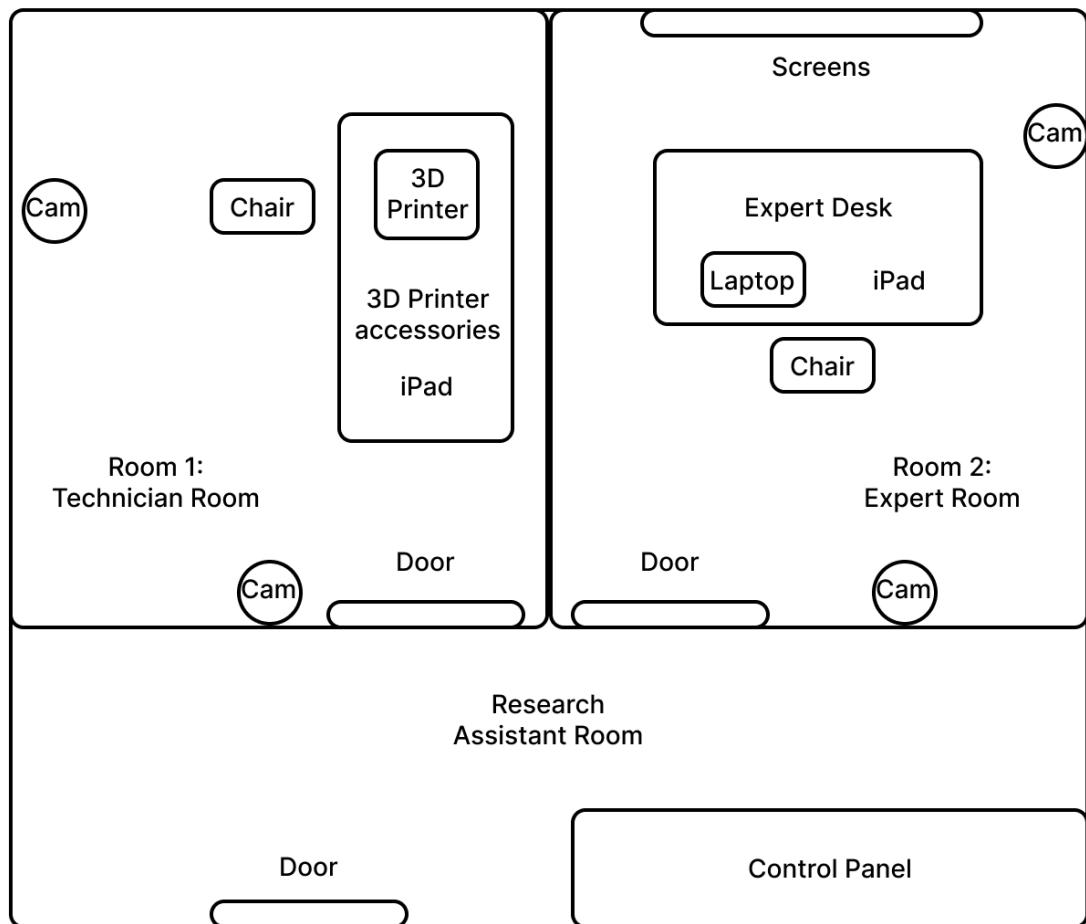


Figure 3. Digital Meetings Lab Setting

Legend: Cam = Camera

A standardized welcome protocol was then read aloud, describing the study's purpose and structure. Afterward, participants were provided with two copies of the consent form to read and sign. Once consent was confirmed, they completed a pre-task questionnaire on an iPad, which

collected demographic information and familiarity with MR devices, applications, and 3D printers, among other data.

Following the questionnaire, participants completed a brief multitasking game designed to assess their level of multitasking, after which they received a short training session to ensure familiarity and comfort with the experimental technology.² The training included a device demonstration for both expert and technician roles, where participants were shown how to operate the assigned communication device either the Microsoft HoloLens 2 for the MR condition or the iPad Mini for the videoconferencing condition.

Next, a training activity was conducted to ensure participants were aware and comfortable with the technology:

- **Device training:** Both expert and technician were shown how to use the assigned communication technology, either the Microsoft HoloLens 2 for the MR condition or the iPad Mini for the videoconferencing condition.
- **Expert training:** The expert received instructions on how to conduct the training task for later guiding the technician through the communication tool (see **Appendix C**).
- **Training task:** The expert then guided the technician through the communication tool on how to assemble the 3D printer for both to get familiarized with the technology.

After completing the training task, the main task was initiated. The expert received again another training on the task, while In MC sessions, technicians underwent additional MC training, where they were instructed to answer arithmetic math questions through a secondary mobile device (iPhone 16 Pro). The technician was told to avoid mentioning the MC task to the expert to evade possible bias. Then, both participants followed a standardized task guide, where the expert

²This information was originally collected as part of the doctoral research conducted by PhD student Edward Opoku-Mensah under the supervision of Professor Ann-Frances Cameron at HEC Montréal and is outside of the scope of this MSc thesis.

instructed the technician step-by-step on how to conduct a task using the 3D printer. All interactions were video- and audio-recorded for later behavioral analysis.

Once the main task was completed, participants filled out a post-task questionnaire on the iPad. At the end of the session, participants received compensation for their participation. A standardized debriefing script was read, reminding participants not to discuss the experiment details with others to prevent information bias in future sessions.

4.5 Instruments

To ensure consistency and precise data collection, the experiment was conducted using a combination of specialized hardware and software tools. The setup was designed to simulate real-world remote assistance scenarios while allowing controlled manipulation of communication conditions (MR, videoconferencing, and with or without MC). All instruments were installed and operated within the Digital Meetings Laboratory at HEC Montréal, which provided a stable and fully equipped environment for running the experimental sessions.

Hardware:

- Digital Meetings Laboratory at HEC Montréal: The laboratory consists of two soundproof experimental rooms equipped with high-quality recording and display systems, meeting all requirements for controlled studies.
- Microsoft HoloLens 2: Used as the MR device for the MR condition, allowing participants to visualize annotations and spatial cues in real time.
- iPad Mini: Served as the primary device for the videoconferencing condition, enabling participants to receive remote expert guidance through Microsoft Teams.
- iPhone 16 Pro: Used for the MC condition delivering timed communication interruptions through automated messages.
- Creality Ender 3 V3 SE 3D Printer: Served as the central task device for the remote assistance activity, allowing participants to perform realistic assembly tasks.
- 3D Printer Accessories: Included necessary components and tools to ensure realistic maintenance and assembly tasks during the experiment.

- Video and Audio Capturing Cameras: Installed in both rooms to record participant interactions and communication behaviors for post-analysis.
- Display Screens (TVs): Used for real-time observation and supervision of the experimental sessions by the research team.
- iPads: Provided to participants for completing pre-task and post-task questionnaires digitally using Qualtrics.
- Laptops: Used by remote experts to deliver instructions.

Software:

- Microsoft Teams: Employed for the videoconferencing condition to enable synchronous communication between the expert and the technician.
- Kognitiv Remote Spark App: Used to conduct the MR remote assistance condition, supporting annotations and spatially aligned guidance.
- Multitasking Game: A computer browser game designed to evaluate the user's multitasking level.
- n8n: Workflow automation software used to automate the timing and delivery of multitasking messages during the experiment.
- Viso: Utilized for synchronized video recording.
- The Observer XT: Used for detailed video analysis and behavioral coding, allowing categorization and quantification of communication behaviors across conditions.
- SAS OnDemand for Academics: Used for statistical analysis, enabling descriptive, correlational, and inferential analyses of the experimental data collected.
- Qualtrics: Used to administer all consent forms, demographic surveys, and pre- and post-experiment questionnaires to participants.

4.6 Analysis Strategy

The analysis of the collected data aimed to test the research hypotheses and examine how MC and communication technology (MR vs. videoconferencing) influenced user experience and communication behaviors. The occurrences of each coded behavior were quantified by reviewing all task recordings in The Observer XT software. These behavioral data were then combined with

participants' questionnaire responses, including the System Usability Scale (SUS) scores and familiarity measures, to enable statistical analysis.

To test hypotheses, all quantitative analyses were conducted using SAS OnDemand for Academics. Descriptive statistics were first calculated to summarize key variables across conditions. Subsequently, Analysis of Variance (ANOVA) tests were performed to identify significant differences between experimental conditions (MR, videoconferencing, and MC) in terms of perceived usability and communication behaviors.

These analyses allowed for the evaluation of both the main effects of communication technology and the interaction effects of MC on the dependent variables. All statistical tests were conducted with a significance level of $p < .05$.

Chapter 5: Analysis and Results

This chapter presents the results obtained from the analysis of experimental data and outlines the analytical procedures used to address the study hypotheses. Both quantitative and behavioral data were analyzed to examine how communication technology (MR vs. videoconferencing) and MC conditions (MC vs. no MC) influenced perceived usability and communication behaviors during remote assistance.

Section 5.1 provides a descriptive overview of participants' demographics and familiarity with the experimental setup, followed by descriptive statistics of usability and behavioral metrics. Sections 5.2 through 5.4 report the inferential results for each hypothesis, examining the main effects of communication technology and MC, as well as their interaction effects on usability and communication efficiency.

5.1 Descriptive Analysis

5.1.1 Demographics and Familiarity by Role

In total, 40 experimental sessions were conducted, involving 80 participants. However, four sessions were discarded due to technical issues such as repeated internet connection losses or temporary power outages on campus. To maintain data quality and ensure the validity of the results, datasets from these sessions were excluded from the analysis. Consequently, the final dataset comprised 36 sessions with 72 valid participants whose data met all experimental criteria. A summary of the participants' demographic characteristics is presented in **Table 2**.

Among the 72 participants, 43 were female (59.7%) and 29 were male (40.3%), indicating a moderately balanced gender distribution. Regarding age, the largest proportion of participants (44.4%) were between 18 and 24 years old, followed by 33.3% between 25 and 34 years old. Smaller groups included participants aged 35–44 years (11.1%), 45–54 years (4.2%), and 55 years and older (6.9%). This age profile suggests that the participant pool was predominantly composed of young adults.

Table 2. Demographic Statistics

Baseline characteristic (n=72)	Frequency	Percentage
Gender		
Male	29	59.72
Female	43	40.28
Age		
18-24 years old	32	44.44
25-34 years old	24	33.33
35-44 years old	8	11.11
45-54 years old	3	4.17
55 years and over	5	6.94
Education		
CEGEP / College	8	11.11
Bachelor's	33	45.83
Master's	24	33.33
Ph.D.	5	6.94
Other	2	2.78

In terms of education, nearly half of the participants (45.8%) held a bachelor's degree, while 33.3% had obtained a master's degree. Additionally, 11.1% had completed college (CEGEP) education, 6.9% held a Ph.D., and 2.8% reported other educational backgrounds. Overall, the participants were well-educated, aligning with the study's focus on individuals capable of engaging in complex technological and collaborative tasks.

Participants' familiarity with the technologies used during the experiment tasks was also captured (see **Table 3**). Because the experimental design involved two distinct user roles, technician and expert, each role's familiarity with technology was analyzed separately. Regarding familiarity with MR applications, both groups reported low experience overall. Among technicians, 41.7% rated their familiarity at level 2 and 33.3% at level 3 on the 7-point scale, whereas experts showed a slightly wider range, with 36.1% each at levels 2 and 3 and smaller proportions at higher levels (4–6).

Table 3. Familiarity Statistics by Role

Baseline characteristic (n = 72)	Technician (%)	Expert (%)
Familiarity with MR Applications		
1	5.60	11.10
2	41.70	36.10
3	33.30	36.10
4	16.70	8.30
5	2.80	5.60
6	0	2.80
7	0	0
Familiarity with 3D Printers		
1	66.70	47.20
2	25	22.20
3	2.80	13.90
4	0	11.10
5	2.80	2.80
6	0	2.80
7	2.80	0

Familiarity with MR Headsets

1	2.80	2.80
2	11.10	8.30
3	33.30	2.80
4	13.90	27.80
5	19.40	44.40
6	19.40	5.60
7	0	8.30

For familiarity with 3D printers, most technicians demonstrated low experience, with 66.7% selecting level 1, followed by 25% at level 2. Experts, by contrast, displayed more variation: 47.2% reported level 1, while the remaining participants were distributed across higher levels (2–6). This distribution is consistent with the intended remote assistance scenario, in which technicians are expected to have limited prior expertise and rely on remote experts for guidance.

Finally, for familiarity with MR headsets, technicians reported diverse levels of experience. The largest proportion (33.3%) rated their familiarity at level 3, representing moderate experience, while 19.4% each rated levels 5 and 6, indicating relatively advanced familiarity. Experts exhibited overall higher familiarity, with 44.4% at level 5 and 27.8% at level 4, indicating stronger prior exposure to immersive hardware.

In summary, the participant demographics reflect a relatively balanced gender distribution and a predominantly young, well-educated sample. Beyond demographic characteristics, the results also indicate moderate to low overall familiarity with MR systems, with noticeable variations between the two user roles. Technicians generally demonstrated limited prior experience, particularly with MR applications and 3D printers, while experts exhibited slightly higher familiarity levels across all technologies.

5.1.2 Descriptive Statistics of Perceived Usability

The descriptive statistics for usability perception, measured using the System Usability Scale (SUS), are presented in **Table 4** and **Table 5**. Both tables show the mean, standard deviation, minimum, median, and maximum SUS scores for technicians and experts across the MC and communication technology conditions.

Table 4. SUS Scores by MC Condition

Role	MC	N	Mean	SD	Minimum	Median	Maximum
Technician	No	18	71.81	20.25	22.5	71.25	100
	Yes	18	73.19	16.6	42.5	77.5	97.5
Expert	No	18	79.44	15.4	30	81.25	97.5
	Yes	18	74.31	16.56	30	75	95

Table 5. SUS Scores by Communication Technology

Role	Technology	N	Mean	SD	Minimum	Median	Maximum
Technician	iPad	18	73.89	18.36	42.5	77.5	100
	HoloLens	18	71.11	18.59	22.5	70	97.5
Expert	iPad	18	72.64	18.82	30	78.75	97.5
	HoloLens	18	81.11	11.54	57.5	82.5	95

When comparing the MC conditions, technicians reported similar usability ratings between both scenarios. The mean SUS score was 71.81 (SD = 20.25) for the no-MC condition and 73.19 (SD = 16.60) for the MC condition. Experts showed a slightly different trend, with higher usability in the no-MC condition (M = 79.44, SD = 15.40) compared to the MC condition (M = 74.31, SD = 16.56).

For the communication technology condition, technicians rated the iPad slightly higher ($M = 73.89$, $SD = 18.36$) than the HoloLens ($M = 71.11$, $SD = 18.59$). In contrast, experts rated the HoloLens higher ($M = 81.11$, $SD = 11.54$) than the iPad ($M = 72.64$, $SD = 18.82$).

5.1.3 Descriptive Statistics of Communication Behaviors

The descriptive statistics for communication behaviors are presented in **Table 6** and **Table 7**, showing the mean, standard deviation, minimum, median, and maximum values for all measured behaviors under both the MC and communication technology conditions. The four behaviors analyzed include Repetition Requests, Wait Requests, Field of View (FOV) Adjustment Requests, and Correctional Communications.

Table 6. User Behaviors by MC Condition

MC	Variable	N	Mean	SD	Minimum	Median	Maximum
No MC	Repetition Request	18	0.17	0.38	0	0	1
	Wait Request	18	0.61	1.14	0	0	4
	FOV Adjustment Request	18	5.5	3.62	0	5.5	13
	Correctional Communication	18	3.44	2.25	0	3	7
MC	Repetition Request	18	1.11	1.78	0	0.5	7
	Wait Request	18	2.89	6.33	0	2	25
	FOV Adjustment	18	6.89	6.09	0	5.5	18
	Correctional Communication	18	5.06	3.87	0	4	14

Table 7. User Behaviors by Communication Technology

Device	Variable	N	Mean	SD	Minimum	Median	Maximum
iPad	Repetition Request	18	1.06	1.76	0	0.5	7
	Wait Request	18	3.44	6.17	0	2	25
	FOV Adjustment	18	6.83	5.18	0	7	18
	Correctional Communication	18	4.83	4.05	0	4.5	14
HoloLens	Repetition Request	18	0.22	0.55	0	0	2
	Wait Request	18	0.06	0.24	0	0	1
	FOV Adjustment	18	5.56	4.84	1	4	17
	Correctional Communication	18	3.67	2.09	1	3	8

When examining the MC condition, participants exhibited more frequent communication behaviors during MC sessions compared to non-MC sessions. The average of Repetition Requests increased from 0.17 (SD = 0.38) in the no-MC condition to 1.11 (SD = 1.78) under MC. Similarly, Wait Requests rose from 0.61 (SD = 1.14) to 2.89 (SD = 6.33), indicating that users needed more time to process when managing multiple communication streams. The frequency of FOV Adjustments also increased from 5.50 (SD = 3.62) to 6.89 (SD = 6.09), suggesting that experts requested to adjust the FOV more often in the presence of concurrent communication. Correctional Communication followed the same pattern, rising from 3.44 (SD = 2.25) in the no-MC condition to 5.06 (SD = 3.87) during MC.

When comparing the communication technology conditions, communication behaviors were more frequent in the iPad than in the HoloLens. On the iPad, participants produced higher averages for Repetition Requests (M = 1.06, SD = 1.76) and Wait Requests (M = 3.44, SD = 6.17) compared to the HoloLens (M = 0.22, SD = 0.55 and M = 0.06, SD = 0.24, respectively). This difference suggests that communication grounding required more verbal coordination in the iPad interaction, likely due to its limited shared visual space. In contrast, FOV Adjustments and Correctional Communication were slightly lower for HoloLens users (M = 5.56, SD = 4.84; M = 3.67, SD =

2.09) compared to the iPad ($M = 6.83$, $SD = 5.18$; $M = 4.83$, $SD = 4.05$), indicating that immersive visualization reduced the need for frequent corrections or repositioning.

5.2 Effects of MR on Perceived Usability and Communication Behaviors

5.2.1 Effects of MR on Perceived Usability (H1)

The first hypothesis (H1) proposed that the use of MR technology during remote assistance would result in higher perceived usability compared to videoconferencing. As shown in **Table 8**, the ANOVA results indicated no significant difference in SUS scores between the MR and videoconferencing conditions for either role. For technicians, the analysis yielded an F-value of 0.21 ($p = 0.6536$), while for experts, the F-value was 2.58 ($p = 0.1179$).

Given that all p-values were greater than 0.05, these results suggest that the perceived usability of MR technology was not significantly higher than that of videoconferencing for either group. Therefore, H1 is not supported in this study.

Table 8. H1 Significance Assessment

Role	F Value	Pr > t	Hypothesis Supported?
Technician	0.21	0.6536	No
Expert	2.58	0.1179	No

5.2.2 Effects of MR on Communication Behaviors (H2)

The second hypothesis (H2) examined whether the use of MR technology during remote assistance would decrease inefficient communication behaviors compared to videoconferencing. Four behavioral measures were analyzed: Repetition Requests, Wait Requests, FOV Adjustments, and Correctional Communication.

As presented in **Table 9**, the results show significant differences for Repetition Requests and Wait Requests, but not for FOV Adjustments or Correctional Communication. Specifically, Repetition Requests were significantly lower when using MR technology ($F = 5.85$, $p = 0.0214$), and Wait

Requests were also significantly reduced ($F = 17.46$, $p = 0.0002$). These findings show support for H2a and H2b, indicating that MR facilitated more efficient communication by reducing the need for repeated or delayed verbal exchanges.

Table 9. H2 Significance Assessment

Variable	F Value	Pr > t	Hypothesis Supported?
Repetition Request	5.85	0.0214	Yes
Wait Request	17.46	0.0002	Yes
FOV Adjustment Request	0.43	0.5152	No
Correctional Communication	0.11	0.7392	No

In contrast, no significant effects were found for FOV Adjustments ($F = 0.43$, $p = 0.5152$) or Correctional Communication ($F = 0.11$, $p = 0.7392$). Thus, there is no support for H2c and H2d, suggesting that these visual or corrective interactions occurred at similar rates across both communication technologies.

Overall, the results partially support H2, confirming that MR technology improved communication efficiency in terms of repetition and waiting behaviors, but did not significantly affect FOV adjustment or correctional exchanges.

5.3 Effects of MC on Perceived Usability and Communication Behaviors

5.3.1 Effects of MC on Perceived Usability (H3)

The third hypothesis (H3) proposed that MC would negatively affect perceived usability during remote assistance. As shown in **Table 10**, the results of the ANOVA test revealed that the effect of MC on usability was not statistically significant for either role. For technicians, the F-value was 0.05 ($p = 0.8223$), and for experts, the F-value was 0.95 ($p = 0.3371$). Both p-values exceed the 0.05 significance threshold, indicating that MC did not significantly reduce perceived usability. Therefore, H3 is not supported in this study.

Table 10. H3 Significance Assessment

Role	F Value	Pr > t	Hypothesis Supported?
Technician	0.05	0.8223	No
Expert	0.95	0.3371	No

5.3.2 Effects of MC on Communication Behaviors (H4)

The fourth hypothesis (H4) examined whether MC would increase process losses, reflected by higher frequencies of communication behaviors. Four dependent variables were analyzed: Repetition Requests, Wait Requests, FOV Adjustments, and Correctional Communication.

As summarized in **Table 11**, the results indicate that MC significantly affected Repetition Requests ($F = 7.02$, $p = 0.0124$), supporting H4b. The mean frequency of Repetition Requests was higher in MC conditions, supporting the prediction that handling multiple communication streams leads to more instances where instructions or information must be repeated.

However, Wait Requests ($F = 3.58$, $p = 0.0675$), FOV Adjustments ($F = 0.20$, $p = 0.6584$), and Correctional Communication ($F = 1.40$, $p = 0.2453$) were not significantly affected by MC. Although Wait Requests approached significance, the effect did not reach the conventional threshold of $p < .05$.

These findings suggest that while MC did not broadly increase all process losses, it specifically led to more frequent Repetition Requests, indicating that the presence of multiple communication channels may increase cognitive load causing loss of focus. Therefore, H4 is partially supported, as only H4b was confirmed.

Table 11. H4 Significance Assessment

Variable	F Value	Pr > t	Hypothesis Supported?
Repetition Request	7.02	0.0124	Yes
Wait Request	3.58	0.0675	No
FOV Adjustment Request	0.20	0.6584	No
Correctional Communication	1.40	0.2453	No

5.4 Moderation Effects of MC on Usability and Behaviors

5.4.1 Moderation of MC on Perceived Usability (H5)

The fifth hypothesis (H5) proposed that MC would moderate the effect of communication technology on perceived usability. As shown in **Table 12**, the results of the ANOVA revealed that the interaction effect between communication technology and MC was not statistically significant for either role. For technicians, the F-value was 2.23 ($p = 0.1448$), and for experts, the F-value was 0.16 ($p = 0.6954$).

Since both p-values exceed the significance threshold of 0.05, the results indicate that MC did not significantly moderate the relationship between communication technology and perceived usability. In other words, whether participants were engaged in MC or not did not alter how they perceived the usability of MR compared to videoconferencing. Therefore, H5 is not supported in this study.

Table 12. H5 Significance Assessment

Role	F Value	Pr > t	Hypothesis Supported?
Technician	2.23	0.1448	No
Expert	0.16	0.6954	No

5.4.2 Moderation of MC on Communication Behaviors (H6)

The sixth hypothesis (H6) examined whether MC moderated the effect of communication technology on process losses, reflected through communication behaviors. Four variables were analyzed: Repetition Requests, Wait Requests, FOV Adjustments, and Correctional Communication.

As summarized in **Table 13**, the interaction effects were not statistically significant for any of the communication behaviors. Repetition Requests ($F = 0.56$, $p = 0.4588$) and Wait Requests ($F = 2.33$, $p = 0.1367$) did not reach significance, indicating that the presence of MC did not alter the frequency of these behaviors across the two communication technologies. Similarly, FOV Adjustments ($F = 0.00$, $p = 0.9491$) and Correctional Communication ($F = 1.35$, $p = 0.2533$) showed no significant moderation effects.

Table 13. H6 Significance Assessment

Variable	F Value	Pr > t	Hypothesis Supported?
Repetition Request	0.56	0.4588	No
Wait Request	2.33	0.1367	No
FOV Adjustment Request	0.00	0.9491	No
Correctional Communication	1.35	0.2533	No

These findings suggest that MC did not significantly influence how communication technology affected behavioral outcomes during remote assistance. The frequency of communication exchanges and visual adjustments remained consistent regardless of whether participants were multicomputing or focused on a single communication stream. As a result, H6 and all its sub-hypotheses (H6a–H6d) are not supported.

Chapter 6: Discussion

This chapter interprets the findings of the experiment by examining how communication technology and MC shaped users' perceptions and behaviors during remote assistance. Building on the statistical results presented in the previous chapter, the following sections connect the empirical outcomes to existing theories and prior research, highlighting both expected and unexpected patterns. The chapter discusses the effects of MR and MC individually and explores whether their influences interact. Finally, the chapter outlines the study's theoretical and practical contributions, acknowledges its limitations, and proposes directions for future research.

6.1 Effects of MR on Perceived Usability and Communication Behaviors

The experiment examined how communication technology (MR vs. videoconferencing) influenced perceived usability and communication behaviors during remote assistance. The results revealed that the use of MR did not significantly increase perceived usability compared to videoconferencing for either role. Both technicians and experts reported comparable SUS scores across the two communication technologies, suggesting that the immersive MR interface did not translate into higher subjective usability. These findings contradict previous studies which have shown that MR remote collaboration systems integrating gestures, gaze, annotations, and other non-verbal cues led to significantly higher system usability compared to traditional methods (Bai et al., 2020; Yan et al., 2023). One possible explanation for this discrepancy could be that in the present study, participants were only able to use annotations, which represent just one of the many visual cues typically available in MR environments. The absence of richer cues 3D virtual objects or hand gestures may have limited the perceived advantages of MR over videoconferencing. Consequently, participants may have perceived videoconferencing as sufficiently usable for the maintenance task, thereby reducing the perceptual gap between the two technologies.

Although the difference in perceived usability was not significant, the results indicated that MR technology significantly improved communication efficiency by reducing certain grounding-related behaviors. Specifically, participants in the MR condition exhibited fewer Repetition Requests and Wait Requests than those using videoconferencing. This suggests that the shared spatial context and visual cues afforded by MR facilitated smoother coordination and reduced the need for verbal clarification. This finding aligns with prior research showing that MR

environments enhance communication efficiency through the integration of non-verbal visual cues that facilitate spatial understanding and coordination. Studies have demonstrated that incorporating cues such as the ones used in the study enables experts to transfer knowledge more effectively to technicians, improving collaboration efficiency, user awareness, and overall user experience in MR-based remote assistance (Yan et al., 2023). This pattern can be further explained through Media Richness Theory, which posits that communication effectiveness increases when the medium provides multiple cues, immediate feedback, and a shared context for meaning (Daft & Lengel, 1986). MR environments offer greater media richness than videoconferencing by providing real-time spatial and visual information that allows users to interpret and respond more efficiently to their partner's actions. The reduction in repetition and wait requests observed in this study therefore reflects how richer communication channels in MR facilitate more efficient grounding and reduce ambiguity in collaborative tasks.

Although participants did not report higher usability for MR, their interaction patterns clearly indicate that the technology had a positive impact. Users in the MR condition relied less on repetition requests and wait requests, suggesting smoother coordination and fewer breakdowns in communication. In other words, even if participants were not consciously aware of an improvement, MR nonetheless supported more efficient grounding and collaboration.

6.2 Effects of MC on Perceived Usability and Communication Behaviors

The results revealed that the presence of MC did not significantly affect perceived usability for either technicians or experts. Participants reported comparable SUS scores under both MC and no-MC conditions, suggesting that engaging in multiple simultaneous communication streams did not alter their overall perception of the technology's usability. This outcome may be explained by the fact that the MR system continued to provide clear spatial and visual cues that supported task coordination even under higher cognitive demand. The visual grounding available through MR may have helped users manage concurrent communication threads without perceiving the added mental effort as a usability decline.

However, MC significantly influenced communication behaviors, leading to an increase in Repetition Requests. This finding indicates that participants required more frequent clarifications when multicommuting, likely due to divided attention and message overlap between concurrent communication channels. This aligns with previous research demonstrating that

multitasking in MR environments can increase mental workload, task prioritization difficulty, and reduce task efficiency (Abbas & Jeong, 2024; Nguyen et al., 2022). When users attempt to manage multiple communication streams simultaneously, their ability to focus and interpret messages accurately becomes strained, leading to coordination breakdowns and the need for additional verbal confirmations. From the perspective of Cognitive Load Theory, managing multiple communication threads simultaneously adds to the user's cognitive processing demand by requiring constant attention switching and working-memory allocation (Sweller, 1988). In MC settings, users must continuously track, interpret, and respond to overlapping information, which can easily exceed their cognitive capacity. As a result, participants in the MC condition exhibited more repetition requests, reflecting the increased cognitive effort needed to maintain communication accuracy and task alignment under multicommutating pressure.

Similar to the findings for MR, the effects of MC reveal a clear divergence between subjective perception and observable behavior. Although participants did not perceive any decline in usability when managing multiple communication threads, their behaviors showed a measurable impact: MC led to more repetition requests and greater need for clarification.

6.3 Interaction Effects Between MR and MC

The analysis revealed no significant interaction effects between communication technology and MC on either perceived usability or communication behaviors. This indicates that the influence of MR and the effects of MC operated independently rather than interactively. In other words, while MR enhanced communication efficiency by reducing grounding-related behaviors, these benefits were not amplified or diminished when participants engaged in MC. Similarly, the additional cognitive demands associated with handling multiple concurrent communication channels did not moderate the usability or behavioral outcomes observed in the MR environment.

One possible explanation for the absence of an interaction effect is that MR's spatial cues supported efficient collaboration but were not strong enough to offset the cognitive strain introduced by multicommutating. While MR helped users coordinate tasks by providing shared spatial context and intuitive visual guidance, these affordances did not reduce mental workload nor prevent the added demands of MC from influencing how participants perceived or behaved with the technology. Following Media Richness Theory and Cognitive Load Theory, the shared

visual context and real-time spatial alignment offered by MR likely supported more intuitive task coordination, which may have buffered the potential negative impact of MC on users' mental workload. Its interface design may have helped maintain manageable cognitive load levels, allowing users to process concurrent communication streams without experiencing a substantial drop in efficiency or user experience.

6.4 Contributions

This study contributes to the growing body of literature on MR, MC, and remote assistance by empirically examining how communication technology and MC influence perceived usability and communication efficiency in remote assistance settings. While prior research has largely focused on comparing MR and traditional systems in controlled settings, few studies have explored how MR performs when users are simultaneously managing multiple communication streams or multitasking. One notable exception is Abbas & Jeong (2024), which investigated the gender factor in multitasking within a MR environment revealing that perceived mental demand is a significant factor in determining how genders perform when juggling multiple tasks, both physical and virtual. A second exception is Nguyen et al. (2022), which explores how short-term absences, caused by interruptions such as phone calls or other distractions, impact user interaction, awareness, and collaboration flow on a remote assistance setting. However, most existing experiments have isolated MR interactions in idealized, single-task contexts, thereby overlooking the cognitive and communicative challenges that arise in real-world work environments (Bai et al., 2020; Huang et al., 2022; P. Wang et al., 2021).

By systematically incorporating MC as an experimental factor within a controlled laboratory design, this study advances existing research by bridging the gap between ecological validity and experimental rigor. Specifically, it demonstrates how real-world communication complexity can be examined under controlled conditions, enabling causal inference while preserving relevance to industrial and remote assistance contexts.

The present study contributes by extending Communication Grounding, Media Richness, and Cognitive Load Theories into immersive and multicommuting contexts. The results highlight how MR's spatial and visual affordances can facilitate grounding and coordination. However, the

added mental workload from managing multiple communication streams remains unchanged, indicating that while MR supports behavioral efficiency, it does not reduce the cognitive demands imposed by MC.

From a practical point of view, the findings provide actionable insights for product designers, engineers, and organizations implementing MR-based remote assistance systems. The results demonstrate that while MR systems do not automatically enhance perceived usability compared to videoconferencing, they significantly improve communication efficiency by reducing redundant and grounding-related exchanges. This suggests that MR can be especially beneficial in scenarios where coordination and precision are critical, such as technical maintenance, manufacturing, and medical support.

Since MC increases clarification needs, this creates opportunities to improve the design and implementation of MR-based systems to better support users operating in multicommuting or high-demand environments. Designers should prioritize features that enhance spatial awareness and provide persistent visual cues that remain available even when users shift their attention to other communication threads. By refining these interaction elements, MR systems can better maintain communication accuracy and coordination under divided attention, without compromising overall usability.

6.5 Limitations

While this study provides valuable insights into the effects of MR and MC on usability and communication behaviors, several limitations should be acknowledged. First, the experiment focused on a single, task-specific scenario involving a technical maintenance activity. Although this controlled approach ensured consistency across conditions, it may not fully capture the variety of cognitive and communicative demands present in real-world remote assistance tasks. MC effects may manifest differently in longer or more complex workflows that require higher task switching or decision-making demands.

Second, the MC condition was simulated using arithmetic questions delivered through instant messages, which provided a standardized form of distraction but may not fully replicate the complexity or unpredictability of real-life MC. In practice, interruptions could involve task-

relevant exchanges, decision-making requests, or emotional communication, which could create different cognitive and behavioral effects.

Third, participants were only able to use annotations which is only one type of visual cue within the MR condition. MR systems typically offer a combination of richer affordances such as gaze, hand gestures, and virtual object manipulation. Restricting interaction to annotations likely limited the potential benefits of MR's media richness, which could explain why perceived usability did not significantly differ from videoconferencing.

Fourth, the sample composition primarily included university students, who may not reflect the experience level or communication styles of professional technicians or experts typically engaged in industrial remote assistance. While undergraduate samples are commonly used because they are easy, fast, and inexpensive to recruit, they also present limitations since they are not representative of broader populations and may produce biased or less generalizable findings (Henrich et al., 2010). Replicating the study with industry professionals would strengthen the generalizability of results.

Finally, the study did not include post-task interviews or qualitative debriefs, relying solely on questionnaires to capture users' perceptions and experiences. Interviews yield a deeper understanding of the phenomenon, resulting in more comprehensive and actionable insights (Dunwoodie et al., 2023). While the quantitative measures provide valuable comparative insights, interviews could have offered deeper, more nuanced understanding of users' communication strategies, challenges, and subjective reactions to MR and MC conditions.

6.6 Future Research

Based on the findings of this study, several areas remain open for further investigation of how MR and MC shape collaborative remote assistance. A first important direction involves examining MR and MC in more complex and extended task scenarios. The present study focused on a single maintenance task, which allowed for controlled comparisons but may not fully capture how cognitive load and communication behaviors evolve during longer, more complex workflows.

A second promising avenue for investigation lies in adopting more realistic and varied forms of MC. The arithmetic-question interruptions used in this study offered a standardized way of inducing divided attention, yet real-world MC often involves far more diverse, unpredictable, and emotionally nuanced demands. Future research should explore interruptions that are task-relevant, time-sensitive, or delivered through multiple channels.

Third, future work should investigate how additional MR visual cues and affordances affect collaboration under MC. Participants in this study only used annotations and gaze, which represent a limited subset of the rich cue combinations that MR systems can offer, such as gestures and 3D virtual objects. Comparing these cues individually or in combination could help determine which affordances best support grounding, reduce ambiguity, or counteract the cognitive demands of MC. This line of research would be particularly useful for informing the design of next-generation MR remote assistance interfaces.

Fourth, further research should involve more industry professionals, real experts with knowledge and experience, who routinely operate in environments with frequent interruptions and high cognitive demands. While student samples offer experimental convenience, they may not reflect the expertise or communication patterns of real maintenance professionals in remote collaboration.

Finally, future research would also benefit from incorporating qualitative methods, such as post-task interviews or debriefing sessions, to complement the questionnaire-based measures used in this study. Conducting interviews could provide deeper insight into users' communication strategies, mental processes, and subjective experiences when operating under MR and MC conditions. This richer qualitative feedback would help uncover nuances that structured questionnaires may not fully capture, offering a more comprehensive understanding of how users perceive with MR-based remote assistance systems.

6.7 Summary

The findings of this study show that while MR did not significantly enhance users' perceived usability compared to videoconferencing, it did meaningfully influence their communication behaviors during remote assistance tasks. MR reduced grounding-related behaviors, such as Repetition Requests and Wait Requests, indicating more efficient communication supported by its

spatial and visual affordances. Similarly, multicomcommunicating did not alter perceived usability but did increase certain behavioral demands, particularly the need for repetition, suggesting higher cognitive load when managing concurrent communication streams. Importantly, no interaction effects were found, meaning that MR and MC influenced user behaviors independently rather than jointly. Taken together, the results indicate that MR primarily improves communication efficiency, whereas MC introduces additional behavioral demands that decrease communication efficiency, and neither influences perceptions of usability.

Chapter 7: Conclusion

This study investigated how MR and MC influence perceived usability and communication efficiency during remote assistance tasks. By comparing MR technology with traditional videoconferencing, and by examining performance under MC and no-MC conditions, the findings contribute new insights into how immersive technologies influence user perceptions and behavioral patterns in realistic, interruption-prone scenarios. Collectively, the results show that while users may not always consciously report differences between communication technologies, their behaviors reveal meaningful patterns that can inform the design of effective remote assistance systems.

The results demonstrate that MR influences communication efficiency in meaningful ways, even when participants do not consciously perceive usability differences. MR significantly reduced wait and repetition requests, suggesting that the spatial cues provided by MR helped streamline interaction and reduce the effort required to maintain mutual understanding in remote assistance. These results highlight the value of MR's visual and spatial affordances in supporting grounding and coordination during collaborative technical tasks.

Technicians had more repetition requests while multicommuting, suggesting divided attention and increased cognitive demand. Although MC did not alter perceived usability, the behavioral evidence indicates that handling multiple concurrent communication streams introduced coordination challenges and increased clarification needs. These findings suggest that MC imposes additional cognitive load on users, which manifests behaviorally rather than through subjective usability ratings.

The analysis revealed no significant interaction effects. This means that the benefits of MR and the added demands of MC operated independently rather than influencing one another. While MR improved communication efficiency, these advantages were not diminished or enhanced when MC was present. Similarly, the additional workload imposed by MC did not affect how users experienced or behaved with MR technology. This pattern suggests that MR's spatial cues support efficient collaboration but do not compensate for the cognitive strain introduced by MC.

Overall, the findings of this study indicate that MR enhances communication efficiency primarily through behavioral improvements, while MC introduces cognitive challenges that surface through increased grounding needs. Yet neither technology nor multitasking condition significantly altered perceived usability. These results show that user behavior can reveal differences between communication technologies even when participants do not consciously report them. Therefore, evaluating remote assistance systems requires looking beyond usability ratings and considering how people interact during the task. Together, they provide a clearer understanding of how MR and MC independently influence user experience and communication dynamics in complex, real-world collaborative environments.

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Appendix

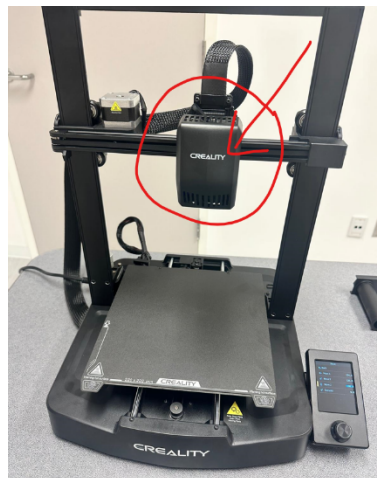
Appendix A. Main Task Instructions

THE TASK (BUILD-PLATE)

What we are going to do right now is that, a student at HEC wants to come use the 3D printer later.
So we have to check the build-plate



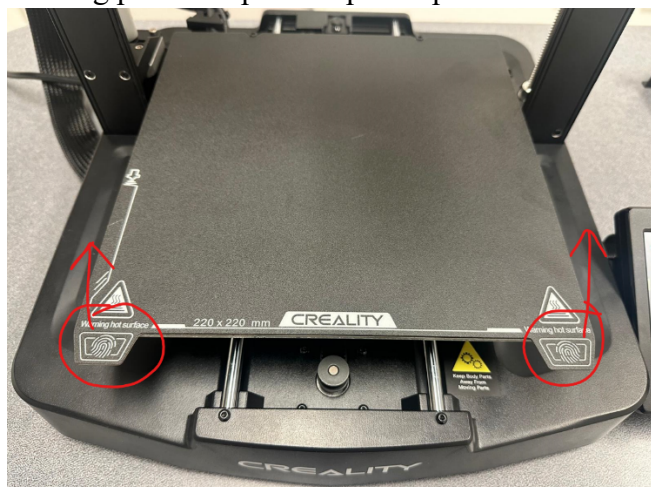
- To be able to move the plate, we need to adjust the **Extruder** to move up, for you to get enough space to remove the plate



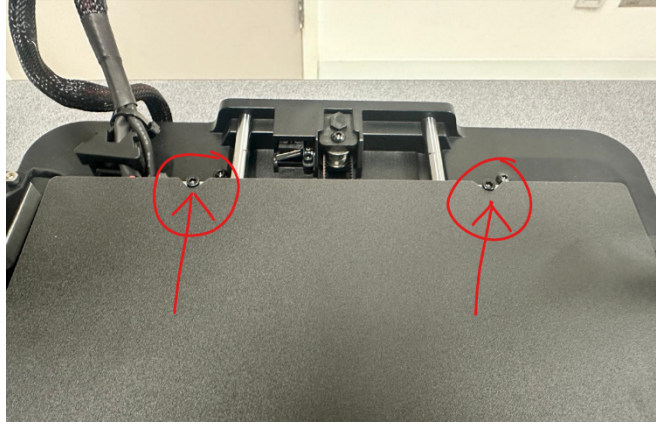
- To adjust the **Extruder**, I need you to check the **Display Screen**.



- Rotate the button to highlight the “**Prepare**” option displayed ON THE MAIN MENU, and push the button down to select
- **If** your see “**Homing**” displayed on the screen, wait for the homing to finish.
- Anytime you see the **3D printer parts moving**, wait for it to stop.
- Rotate the display screen button to select “**Move**” from the options.
- Rotate the display screen button to select “**Move Z**” from the new options
- Now you can rotate the button again to your right (clockwise), to start moving the Extruder upwards.
- Stop rotating when the Move Z reading displays: **170**
- Now, you can proceed to remove the build-plate.
 - It is flexible and rest on the surface like a magnet
 - Hold the protruding parts and pull the plate upwards



- Take a look at the buildplate you are holding in your hands, to see if it looks okay.
- Finally, we are going to put the buildplate back in place.
- Slowly place it from the back into the two screws at the back of the desired position

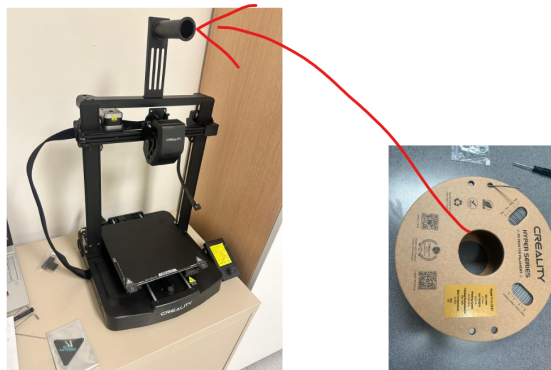


- And make sure all edges fit the surface well.

THE TASK (FILAMENT SWAP)

Another one of our students want to use a filament for printing, let's setup the filament for the student.

- Now take the **filament** and insert it in the **Material Assembly Rack** on top of the printer.
 - And make sure the yellow label on the filament is facing the front side of the printer



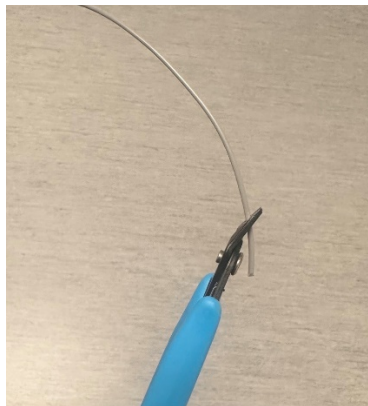
Provide similar annotation to teammate if required

- You need you to check the **Display Screen**.



Provide similar annotation to teammate if required

- Rotate the display screen button to the top of the screen options,
 - And choose **Back** to go back.
- Rotate the button to highlight the “**Prepare**” options displayed, and push the button down to select.
- Rotate the display screen button to choose “**Extrude**”.
- Wait for a few seconds when you see the **Extruder** moving.
- Cut the tip of the filament with a **Cutting plier** at 45 degrees, and throw the cut piece away.



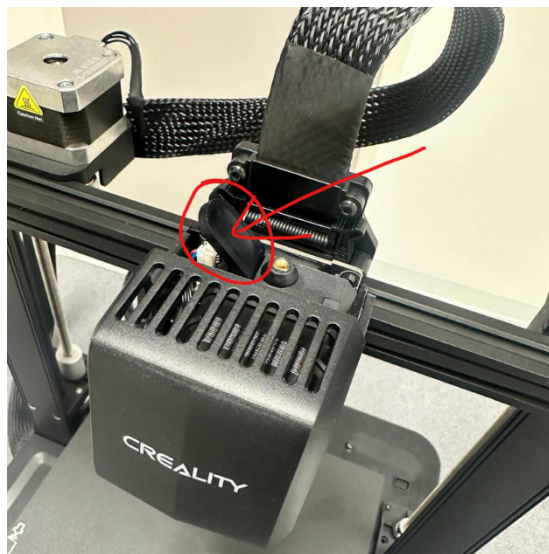
Provide similar annotation to teammate if required

- Now let's focus on the Extruder



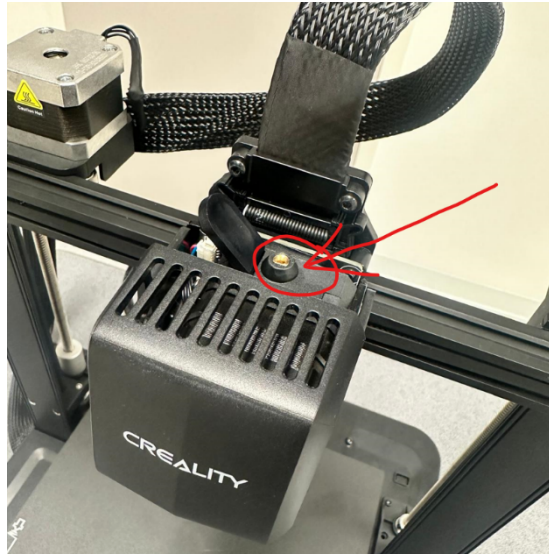
Provide similar annotation to teammate if required

- At the top of the **extruder** push the **extruder lock** downwards and hold it down to allow the filament in.



Provide similar annotation to teammate if required

- Insert the tip of the **filament** into the **extruder hole**.



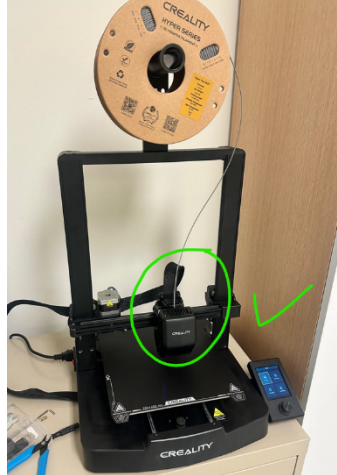
Provide similar annotation to teammate if required

- When you see the **Extruder moving** wait for it to stop moving.



Provide similar annotation to teammate if required

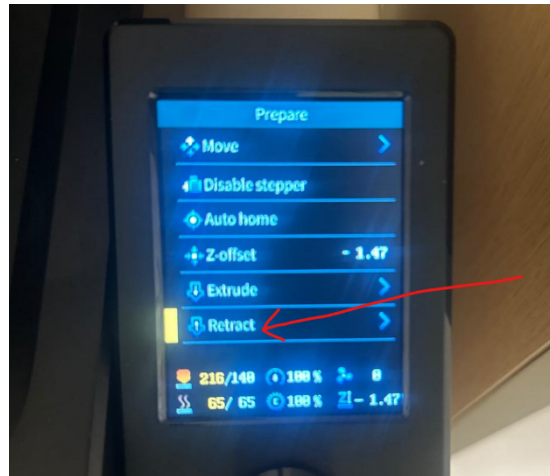
- If you see the **CONFIRM** displayed on the screen, click on it **ONLY ONCES AND WAIT** a few seconds before proceeding.
- Now Push the filament downwards until it hits the bottom of the extruder.



Provide similar annotation to teammate if required

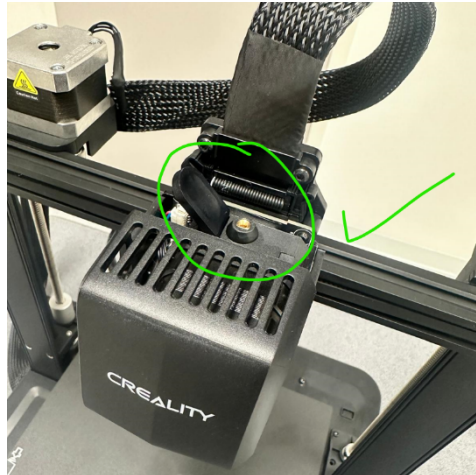
Great, now that we have setup the filament successfully. We are going to remove it, for any other student to use the printer with their own filament.

- From the Display screen, choose **Retract**.



Provide similar annotation to teammate if required

- IF the **Homing** page is displayed, wait for it to finish, to be able to proceed.
- Now when you see the **Retracting** page, wait again for the readings to match the progress levels such as 248/248 or 140/140, etc., **or** when the numbers stop moving to continue.
- The extruder will now slow push the filament out. Once the **pull-out page** is displayed, push the **extruder lock** downwards and remove the filament from the extruder.



Provide similar annotation to teammate if required

- Now push the **display screen button** downwards to confirm, if you see confirm.
- Rotate the display screen button to the top of the screen options,
 - And choose **Back** to go back to the homepage.

This brings us to the end of the task.

Appendix B. System Usability Scale (SUS)

System Usability Scale (SUS)

Brooke, J. (1986). System Usability Scale (SUS): A Quick-and-Dirty Usability Scale. Usability Evaluation in Industry, 189-194.

Scale: 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree)

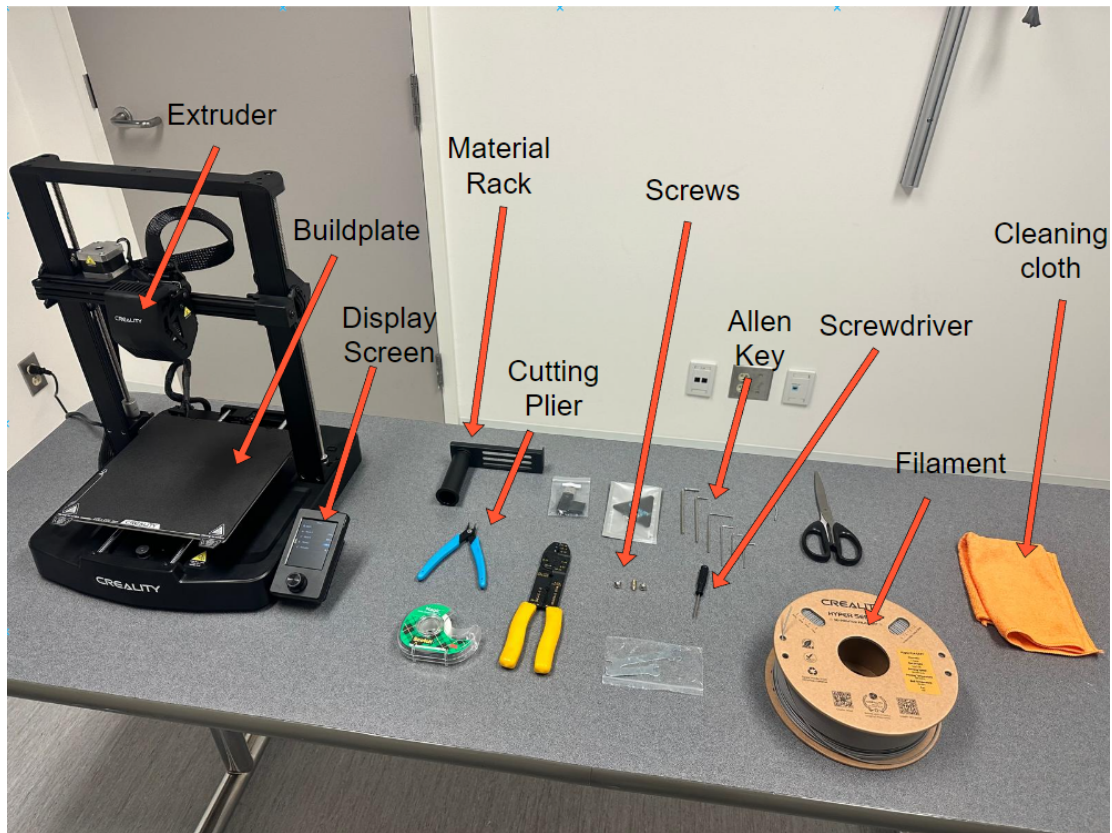
Items:

- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.
- I found the various functions in this system were well integrated.
- I thought there was too much inconsistency in this system.
- I would imagine that most people would learn to use this system very quickly.
- I found the system very cumbersome to use.
- I felt very confident using the system.
- I needed to learn a lot of things before I could get going with this system.

System Usability Scale (SUS) adaptation for this study

- I think that I would like to use this technology frequently.
- I found the technology unnecessarily complex.
- I thought the technology was easy to use.
- I think that I would need the support of a technical person to be able to use this technology.
- I found the various functions in this technology were well integrated.
- I thought there was too much inconsistency in this technology.
- I would imagine that most people would learn to use this technology very quickly.
- I found the technology very cumbersome to use.
- I felt very confident using the technology.
- I needed to learn a lot of things before I could get going with this technology.

Appendix C. Training Task Instructions



All Components and names

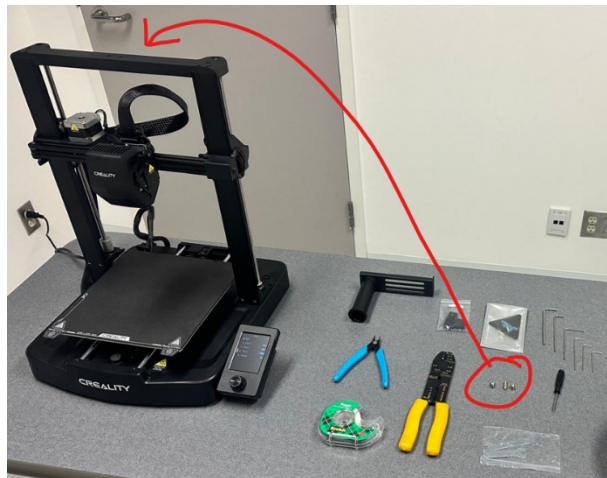
TRAINING TASK

- To begin, you need to take the **Material Rack**.



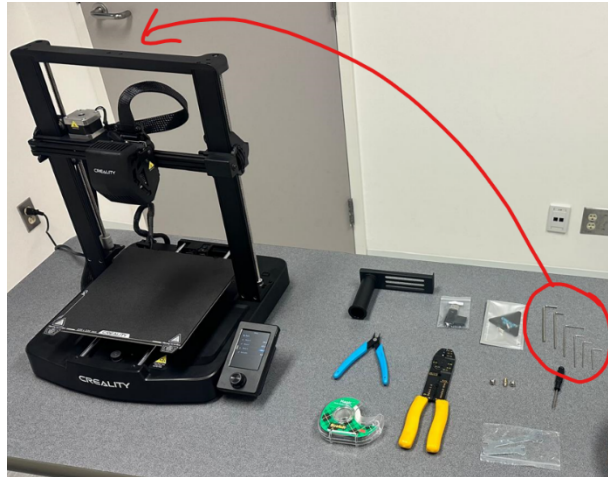
Provide similar annotation to teammate if required

- You also need to take the two identical screws (Hexagon Socket Button Head Screws) to hold it into position.



Provide similar annotation to teammate if required

- Finally, you will need a suitable Allen key, that will be used to screw the material rack tightly into position (It is the second biggest key).



Provide similar annotation to teammate if required

- Place the material rack to stand on the top of the 3D printer, with the pointed side facing the front of the printer.
- Insert the two screws.
- And use the **Allen key** to tighten it into position.



Provide similar annotation to teammate if required