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3D Design Tasks on Interactive Whiteboards: Impacts of Synchronous Manipulation and Individual Spatial Ability

by

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Résumé

Les collaborations virtuelles dans des environnements de conception tridimensionnels sont courantes dans les domaines de l'architecture, de l'ingénierie et de la construction. Nous explorons le potentiel des tableaux blancs interactifs en tant qu'outil d'assistance pour les tâches de conception en 3D, un domaine qui n'a pas fait l'objet d'études approfondies. Cette étude se concentre sur les effets de la synchronisation de la manipulation dans de tels environnements, où plusieurs utilisateurs peuvent simultanément accéder au même objet 3D et le modifier. Nous étudions l'impact de la manipulation synchrone pendant les tâches de conception 3D sur l'expérience de l'utilisateur (y compris les réactions affectives et effectives), la contribution et la performance de la tâche de groupe. Notre expérience en laboratoire avec 82 participants révèle que la synchronisation de la manipulation améliore de manière significative l'expérience de l'utilisateur, la contribution et la performance de la tâche. La capacité spatiale individuelle démontre également des effets de modération significatifs sur les relations entre la synchronisation de la manipulation et la performance de la tâche, ainsi que la synchronisation de la manipulation et la difficulté de la tâche, renforçant ces relations pour les personnes ayant une faible capacité spatiale.

Mots clés : Synchronicité de la manipulation, Collaboration virtuelle, Tableaux Blancs Interactifs, Collaboration 3D, Capacité spatiale individuelle

Méthodes de recherche : Expérience en laboratoire, Questionnaire

Abstract

Virtual collaborations through Three-Dimensional (3D) design environments are commonly seen in architecture, engineering, and construction. We explore the potential of Interactive Whiteboards (IWBs) as a support tool for 3D design tasks, an area that has not been extensively studied. This study focuses on the effects of manipulation synchronicity in such environments, where multiple users can simultaneously access and edit the same 3D object. We investigate the impact of synchronous manipulation during 3D design tasks on user experience (including affective and effective reactions), contribution, and group task performance. Our laboratory experiment with 82 participants reveals that manipulation synchronicity significantly improves user experience, contribution, and task performance. Individual spatial ability also demonstrates significant moderation effects on the relationships between manipulation synchronicity and task performance, as well as manipulation synchronicity and task difficulty, strengthening these relationships for low spatial ability individuals.

Keywords: Manipulation Synchronicity, Virtual Collaboration, Interactive Whiteboards, 3D Collaboration, Individual Spatial Ability

Research methods: Laboratory Experiment, Questionnaire

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List of Abbreviations and Acronyms

IWB (s): Interactive Whiteboard(s)

UX: User Experience

MRT: Mental Rotation Test

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Chapter 1: Introduction

Synchronous virtual collaborations where multiple people work remotely via software/platforms have been proven to be highly beneficial across various fields, enhancing the work processes and outcomes of general work tasks such as co-sketching, co-writing, and 2D object manipulation. For example, studies have highlighted the advantages of synchronous virtual collaborations, which include improved user experiences such as increased satisfaction and pleasure, efficient communication, and increased focus on the task at hand, all leading to enhanced overall performance (Mabrito, 2006; Rahman et al., 2013; Stone et al., 2017; Yim et al., 2017).

The prevalence of synchronous virtual collaborations via video conferencing applications like Zoom and Microsoft Teams has significantly increased since the onset of the pandemic (Marks, 2020). Although people have been returning to in-person work, remote work setups have continued impacting collaboration modes even post-pandemic (Mitchell, 2021; Mitchell, 2022). This large-scale transition from face-to-face to virtual work goes hand in hand with increased use of and investment in virtual collaboration tools and digital technologies (COVID-19, 2021). Individuals and teams increasingly rely on synchronous virtual tools to maintain seamless communication and productivity. As a result, synchronous virtual collaborations have become an integral part of modern work practices across diverse industries, enabling efficient and effective teamwork regardless of physical location.

Three-dimensional (3D) design tasks – common in architecture, engineering, and construction – sometimes also need to be completed virtually. Synchronous virtual collaborations of 3D works can be supported by 3D design environments., which include 3D software and web-based platforms. Some 3D design software and web-based 3D platforms, such as Tinkercad, Solidworks, SketchUp, and Onshape, that have been built to support virtual collaborations. Those tools provide a 3D virtual workspace for distributed team members, which has proven beneficial for virtual 3D collaborations. They increase co-presence awareness, satisfaction, and engagement and facilitate smooth transitions between group work and individual work (Eves et al., 2018; Gül & Maher, 2009; Phadnis et al., 2021; Stone, Salmon, Hepworth, Gorrell, et al., 2017a; Zhou et al., 2020).

Two modes are commonly observed and used in 3D design virtual collaborations when employing 3D design software/platforms. One mode is with synchronous manipulation, such that all group members share control and can manipulate 3D objects in a 3D design environment (e.g., Tinkercad) by moving and editing 3D artifacts simultaneously in the same project. The second is without synchronous manipulation, where only one member has individual control to manipulate objects in the 3D design environment while the other team members participate only by observing through a shared screen (e.g., via Zoom or Microsoft Teams). Thus, we defined *manipulation synchronicity* as the functionality provided by a 3D software or platform to control access to moving and editing a 3D object. Users have requested such multi-user synchronous manipulation to support real-time design collaboration (Cheng et al., 2023; Piegl, 2005).

One tool widely used for collaborative tasks in various settings, such as education and business, is large interactive displays or interactive whiteboards (IWBs). IWBs can increase engagement and motivation (Buisine et al., 2012; Kubicki et al., 2019; Mariz et al., 2017; Valérie et al., 2021) and positively impact collaborative outcomes (Mateescu et al., 2021; Buisine et al., 2012). IWBs are used in both face-to-face and remote collaboration, including the mode mentioned above without synchronous manipulation, where only one individual controls the content, as well as the mode with synchronous manipulation collaborations like co-writing (Yim et al., 2017), co-sketching (Stone, Salmon, Hepworth, Gorrell, et al., 2017b), and manipulating 2D objects in real-time (Rahman et al., 2013). However, no research explores how synchronous manipulation of a 3D objects during virtual 3D design work on IWBs impacts user experience, contribution, and task performance.

1.1 Research Objectives and Questions

In this research, we examine those 3D design tasks being done with a 3D design platform/software (e.g., Tinkercad, Autodesk, Sketchup). The scope of this research includes 3D design collaborations involving more than one team member collaboratively in a 3D design environment to complete group 3D design tasks. According to ISO 9241 – 210 (ISO, 2019), *User Experience* (UX) is "a person's perceptions and responses that result from the use and/or anticipated use of a product, system, or service." Our research focuses on one participant's perceived experience with 3D group tasks, the collaboration process and outcome, and perceived experience with the technologies. We also want to understand how manipulation synchronicity impacts on perceived individual contribution and actual group task performance.

The challenge is understanding the impacts of synchronous manipulation during 3D work in a 3D design environment on IWBs. Some researchers, such as Rahman et al. (2013), emphasize the importance of synchronous manipulation, but the tasks in their experiment involve manipulating 2D objects. There are also many technical articles about supporting 3D real-time collaboration (Du et al., 2016; French et al., 2015; Song et al., 2015), in which they propose and verify cloud-based or web-based platforms' feasibility. However, they do not compare virtual 3D collaborations with synchronous manipulation to those without synchronous manipulation. Phadnis et al. (2021) focus on synchronous manipulation during 3D modeling on distributed computers equipped with keyboards and mice, but do not study IWBs. To further reveal the relationships and benefits of synchronous manipulation on 3D collaborations on IWBs, two research questions are proposed in this research. The first is **RQ 1:** How does synchronous manipulation on an interactive whiteboard influence user experience, contribution, and performance during virtual 3D design work?

Research has also shown that individual characteristics and abilities influence how people use IWBs (Mateescu et al., 2021). The 3D work process usually requires applying spatial ability to move, rotate, and visualize 3D virtual objects. One individual ability that may be particularly important for design work on IWBs is the individual spatial ability, which is a critical factor in 3D tasks (Chang, 2014; Dere & Kalelioglu, 2020; Eves et al., 2018; Froese et al., 2013; Hegarty et al., 2006; Stone, Salmon, Eves, et al., 2017). *Individual spatial ability* is defined as "the ability to generate, retain, and transform abstract visual images" (Lohman, 1979, p. 3). Research has shown that individual spatial ability differs from one person to the next (Mohler, 2008), and people with different spatial abilities use different strategies and have different speeds when processing spatial information (Gages, n.d.).

Previous results on 3D design environments in education indicate that students can learn new strategies when using 3D design environments for spatial tasks, and individuals can perform better by applying those strategies to solve spatial problems (Chang, 2014; Dere & Kalelioglu, 2020; Rafi et al., 2005; Roca-González et al., 2016; Šafhalter et al., 2022). Furthermore, individuals with high and low spatial ability individuals benefit differently. Low spatial ability individuals often improve more on tests involving spatial tasks (Dere & Kalelioglu, 2020; Froese et al., 2013). These findings lead to our second research question, **RQ 2:** How are the effects of synchronous manipulation on a 3D design task moderated by an individual's spatial ability?

Drawing on previous research results and theory, we have developed hypotheses related to these two research questions. To verify our hypotheses, we followed a confirmatory experimentation process, including reviewing previous works, building a research model, designing an experiment, conducting the experiment, analyzing data, interpreting results, and generating implications for practice and research. For the experiment, we recruited 82 participants to our lab, where it is easier to control experimental conditions. Data were collected during and after the experiment. Individual spatial ability was measured by a standard test, Mental Rotation Test (MRT), and subjective data were collected through self-reported questionnaires. The behavior measure is group task performance on the 3D design task, which was graded by the researcher according to a grading scheme.

1.2 Contributions

Our research makes a valuable contribution to academic research on virtual collaboration, focusing on three key aspects: 3D tasks on IWBs, synchronous manipulation, and individual spatial ability. In the following paragraphs, we delve into each of these aspects.

The first significant academic contribution lies in our study of 3D tasks completed on IWBs. Unlike other authors who have primarily explored general virtual collaborative tasks on IWBs, such as brainstorming (Siemon et al., 2017), and remote 2D object manipulations (Zillner et al., 2014), our research centers on 3D tasks performed virtually on IWBs. Previous studies have found that IWBs facilitate virtual collaboration and contribute to increased motivation and satisfaction, decreased frustration and effort, and performance improvements (Siemon et al., 2017; Zillner et al., 2014). Extending their findings, our research introduces a 3D group design task, enabling us to offer a deeper understanding of user experience, individual contribution, and performance during 3D work on IWBs.

While previous research has explored 3D tasks on desktops, tablets, AR/VR equipment, and other platforms, there appears to be a dearth of studies investigating those tasks on IWBs. Previous research found that collaborations in those environments are immersive, can improve participation equality, and improve performance (Gu et al., 2011; Hong et al., 2016; Phadnis et al., 2021; Schouten et al., 2016). The research by Phadnis et al. (2021) also discusses 3D collaboration with and without synchronous manipulation; however, their experiment was completed on computers with keyboards and mice. We aim to expand the research findings on 3D collaborations to the context of IWBs.

The second significant academic contribution of our research focuses on the collaboration mode, expanding research on synchronous collaboration to include the notion of synchronous manipulation. Existing research has compared synchronous and asynchronous collaborations, where all team members collaborate in real-time (such as via video conferencing tools) versus at different times (such as via email). These studies have found that synchronous collaboration generally leads to a more positive experience, resulting in higher levels of satisfaction, pleasure, lower frustration, and increased enjoyment (Mabrito, 2006; Rahman et al., 2013; Stone et al., 2017). This positive experience is attributed to the fact that team members can interact directly and frequently with the software and their partners in real-time. There are mixed findings regarding performance improvements (Deng et al., 2022; Phadnis et al., 2021; Rahman et al., 2013a).

In our study, we go beyond simply synchronous collaboration to explore synchronous *manipulation*. Although we found one study by Rahman and colleagues (2013) that briefly touched on the importance of synchronous manipulation, their investigation primarily focused on manipulating 2D objects. Building upon their results, our research aims to conduct a more in-depth comparison between 3D collaboration modes with and without synchronous manipulation. Stone and colleagues (2017) researched multi-user computer-aided design by comparing it with individual computer-aided design over 3D design tasks, finding significant advantages of synchronous collaboration; however, they also involved different roles, such as managers who do not manipulate a 3D object directly. Our study focuses on users who need to manipulate virtual 3D objects themselves. By exploring this aspect, we shed light on the distinct advantages and drawbacks of using synchronous manipulation during collaborative tasks. Our goal is to contribute to the existing knowledge and understanding of the impact and effectiveness of synchronous manipulation in enhancing the overall collaboration experience and performance in a 3D virtual environment.

The third significant academic contribution of our research pertains to the investigation of the impacts of spatial ability during group 3D tasks. As spatial ability varies among individuals due to the use of different strategies in processing spatial information (D'Oliveira, 2004), it has been identified as a potential predictor of performance in complex cognitive tasks (Barrera Machuca et al., 2019; Cohen & Hegarty, 2007). In our study, we have incorporated spatial ability as a moderator to understand the differences between individuals with high and low spatial ability when using synchronous manipulation for 3D work. Previous research on spatial ability has primarily involved individual experiment tasks designed to test whether spatial training through 3D software or VR/AR environments can improve an individual's performance on spatial tasks. These studies have shown that spatial task performance can indeed be improved (Dere & Kalelioglu, 2020; Froese et al., 2013; Rafi & Samsudin, 2009; Roca-González et al., 2016). Furthermore, they have discovered that the impact of spatial training varies based on an individual's level of spatial ability, with those possessing low spatial ability benefiting greater from 3D training (Chang, 2014; Dere & Kalelioglu, 2020; Froese et al., 2013). These findings have laid a solid foundation for our research hypotheses, and we aim to contribute by adding our findings in the context of 3D collaborative design. Our findings contribute to a better understanding of 3D collaborative design tasks and spatial abilities research.

Our research also aims to make several meaningful contributions to practice. For 3D designers, our findings will provide valuable insights that can further validate the challenges they face with synchronous manipulation, particularly for individuals with low spatial ability, as indicated in existing research (Chang, 2014; Dere & Kalelioglu, 2020; Froese et al., 2013). By understanding these pain points, designers can recognize the potential for improvement in their experience, individual contribution, and overall performance during virtual 3D work on IWBs or other large interactive displays through the adoption of 3D design software/platforms equipped with synchronous manipulation.

As the significance and benefits of synchronous manipulation become more widely recognized, companies will adapt their internal managerial strategies to capitalize on these advantages.

Business owners and 3D project managers will gain awareness of how synchronous manipulation and individual spatial ability significantly influence UX, contribution, and group work performance. By incorporating tools with synchronous manipulation into their workflows, companies can foster positive experiences for their employees, elevate their contribution levels, and enhance overall business value.

Furthermore, our research will serve as a persuasive factor for 3D product/service providers. It will help them understand the importance of synchronous manipulation during virtual 3D collaborations, highlighting the evident benefits of integrating this functionality into their platforms. By recognizing the importance of synchronous manipulation, providers can enhance their 3D design platforms used on IWBs, thereby catering to the evolving needs and preferences of designers, collaborators, and users in 3D design environments. Overall, our research seeks to bridge the gap between academic exploration and practical application, providing a comprehensive understanding of the impact of synchronous manipulation and individual spatial ability in 3D design collaborations.

Table 1 *Student Contribution and Responsibilities in the Realization of this Thesis*

Research Process	Student Contribution
Research Question	Identification of objectives relating to the themes of synchronous manipulation during 3D design work on IWBs. Defining the research problem. – 60% * I received advice from my supervisors on how to discover research gaps and find the most interesting and worthy research problem; how to define a research question; and how to identify constructs.
Literature Review	Review of academic articles – 90% Writing literature review – 100% * I received constant feedback from my supervisors on how to structure and modify this section accordingly.

Research Process	Student Contribution
Experimental Design	Experimental design and procedure – 80% * My experiment was the first to be performed in Dr. Cameron’s Digital Meetings Lab, so I developed the experimental design and procedure, modifying it as necessary according to the suggestions given by my supervisors. * I set up my experimental 3D environment in Tinkercad with assistance from Wendi Hu with the creation of 3D buildings.
Recruitment	Recruitment of participants for studies – 80% * I conducted the entire recruitment process of the participants with help from my supervisors and colleagues from the Digital Meetings Lab. The participants were recruited via the Panelfox research panel administered by the Tech3Lab for HEC Montréal.
Laboratory Experiment	Moderated 41 experiment sessions with 82 participants –85% * I received help from one PhD. student (Edward Opoku-Mensah) and one M.Sc. student (Thibault Bouchardie) as research assistants.
Data Analysis	Excel data cleaning, combination, and formatting – 90% Analysis of results performed using SPSS – 80% - Analyzing reliability using SPSS. - Hypothesis analysis using t-test and factor analysis. Results interpretation – 70% * I received help from my supervisors with analyzing the data and interpreting the results.

Research Process	Student Contribution
Thesis Writing	Writing my thesis – 100% * My two (2) supervisors guided me through the entire process with detailed feedback, allowing me to make the appropriate changes to improve the overall quality of my thesis. My work was edited by an English language editor for within-sentence improvements.

1.3 Thesis Structure

This thesis is structured in a classic format. In Chapter 1, the introduction, the general context, and the research objectives are briefly presented. Chapter 2 contains a literature review covering the topics related to synchronous manipulation during 3D work in 3D design environments on IWBs. Chapter 3 addresses the theoretical foundations and hypotheses development, and Chapter 4 discusses the methodology. Chapter 5 presents and interprets the experimental results. Finally, Chapter 6 includes the discussion and conclusion section of the thesis.

Chapter 2: Literature Review

This literature review focuses on topics related to synchronous manipulation during virtual 3D design collaborations on interactive whiteboards (IWBs) and the influence of individual spatial ability. A comprehensive review was conducted, encompassing relevant studies from education, architecture, engineering, construction, and creative design. This chapter presents the findings and research gaps related to our research questions.

Synchronous manipulation in this research is a functionality provided by design software or web-based platforms like Google Docs, Tinkercad, and Onshape to support synchronous virtual collaborations, where multi-users can not only view but also edit the same objects in a project file at the same time from different locations, thereby having all group members with shared control. In contrast, a virtual collaboration environment without synchronous manipulation allows only one individual to have control and other team members are guests who share the same view as the one with individual control. This is achieved via the screen-share functions provided by video conferencing software such as Zoom and Microsoft Teams.

This literature review aims to investigate previous findings regarding how synchronous manipulation impacts virtual 3D group collaborations on IWBs. Existing research about three impacts was reviewed: User Experience (UX), contribution, and task performance. UX includes affective reactions presented as perceived frustration, satisfaction, enjoyment, engagement, as well as effective reactions that include perceived task difficulty, efficiency, and ease of use. Contribution includes perceived contribution level, contribution frequency, participation equality, and general contribution behavior. Task performance includes perceived and actual group task performance.

2.1 Synchronous Manipulation in Virtual Collaborative Work

We reviewed the literature which related to synchronous manipulation in the area of general virtual collaborative work, virtual collaborative 3D design task, and such tasks done on IWBs. See the table in Appendix A for a more detailed analysis of the relevant articles.

2.1.1 Synchronous Manipulation in General Virtual Collaborative Work

Previous research has investigated general tasks completed with synchronous manipulation in virtual environments like co-writing, co-sketching, and brainstorming. As will be described below, most of these studies have indicated synchronous manipulation enhances UX, contribution, and task performance. This improvement is attributed to enhanced co-presence, efficient communication, and increased focus on the task, collectively leading to enhanced overall performance.

Regarding the affective reactions, Gül and Maher (2009) researched collaborative sketching in a virtual environment, finding that synchronous manipulation in virtual collaborations has positive impacts, such as being perceived as engaging, satisfying, and comfortable. Stone et al. (2017) successfully developed and tested a 2D synchronous co-sketching application called Telestrator, discovering that using a synchronous co-sketching application can increase user enjoyment and reduce frustration. Additionally, Rahman et al. (2013) investigated 2D-object manipulation tasks in a virtual collaboration platform, finding that synchronous work mode generates more satisfaction than asynchronous. Mabrito (2006) examined co-writing via shared word-processing platforms, and the results revealed that 100% of the students from the experiment preferred synchronous editing, while only 50% liked asynchronous editing. The students also reported that synchronous writing sessions were more comfortable than asynchronous ones.

In terms of effective reactions, participants in the experiment conducted by Stone et al. (2017) expressed that the synchronous sketch application makes it easier to contribute and more effectively understand their teammates' ideas when sketching simultaneously, as opposed to an audio-only context. Yim et al. (2017) explored co-writing, highlighting that a synchronous collaborative writing environment draws attention to group writing and efficiently supports more members to work on the article, producing longer articles. Furthermore, participants from research conducted by Mabrito (2006) reported that they discussed efficiently when the collaboration was synchronous.

Although prior research has not emphasized synchronous manipulation, the researchers have investigated synchronous *collaborations* that provide all team members equal access to contribute, and these studies have indicated that synchronous collaboration does indeed improve equality of contribution. For instance, Telestrator, a collaborative sketching application developed by Stone et al. (2017), allows all users to sketch and view their team members' progress through mouse movement. The author concludes that Telestrator can improve the perceived equality of teammate contribution during virtual 2D co-sketching, as members can virtually see their partners' actions in real time. Mabrito (2006) and Yim et al. (2017) mentioned similar findings regarding equality of teammate contribution. Yim et al. (2017) found that the synchronous feature allows for more balanced participation, while Mabrito (2006) found that the team members engage in more active discussions and contributions under synchronous conditions.

Due to the positive effects of synchronous collaboration on experience and contribution, some research has shown that task performance is also improved. For example, Yim et al. (2017) conclude that students with different abilities can refine the paper together to achieve better grades when all members can write simultaneously. Rahman et al. (2013) pointed out that synchronous manipulation could increase interaction quality, and users perceive better team performance on the group task. However, contrasting findings were presented by Mabrito (2006), who found that team members under synchronous conditions perceived the collaboration as less productive than in asynchronous conditions. This was attributed to real-time discussions occasionally deviating from the writing task, while asynchronous comments remained more focused on the writing task.

Furthermore, Rahman and colleagues specifically emphasize the importance of "shared activity (NOT shared-view), the ability to manipulate together, and that such a common activity space is most relevant for the success of the idea generation phase" (2013a, p. 420). This article emphasizes that providing shared manipulation access, not providing a shared view, contributes to better performance. The author explains that remote work often implies that people work independently and need to control objects by themselves. The research also points to a research gap: to study "synchronous communication versus the synchronous object manipulation of design artifacts" (2013, p. 422), which we are interested in investigating in our research. We aim to compare the different UX and collaboration outcomes between contexts with shared manipulation and a shared view. We extend their research on 2D object manipulation to 3D works.

2.1.2 Synchronous Manipulation in Virtual Collaborative 3D Design Tasks

The scope of the 3D design tasks in this literature review covers cases involving multiple team members collaboratively manipulating 3D objects in a 3D design environment. The tasks could include rotating or relocating 3D objects to present a spatial layout or to complete 3D modeling. Those tasks are cognitively demanding and rely heavily on the affordance of the 3D design environment technology setup. We have found several relevant articles addressing synchronous manipulation in 3D design environments.

During 3D design tasks, such as 3D modeling and decision-making for 3D design solutions in a 3D design environment with synchronous manipulation, users tend to experience more intense affective reactions. Zhou et al. (2020) studied the emotions arising from virtual 3D collaborations. They concluded that, on average, individuals working in groups experience higher levels of mixed emotion (including joy, sadness, anger, contempt, fear, and surprise) than those working individually. In contrast, Phadnis et al. (2021) investigated 3D modeling with Onshape by comparing individual, "single shared input" (the equivalent of without synchronous manipulation in our research), and "parallel collaboration" (to the equivalent of with synchronous manipulation in our research). They found that synchronous manipulation does not lead to higher satisfaction during the collaborations than "single shared input" (without synchronous manipulation).

For effective reactions, similar to the research findings of synchronous manipulation during the general tasks discussed in the previous section (2.1.1), a synchronous virtual collaboration environment is capable of supporting communication efficiency. Phadnis et al. (2021) found that both paired work modes ("single shared input" and "parallel collaboration") lead to more frequent communication than individual mode, and the two paired modes increased members' awareness of each other. Similarly, Eves (2018) concluded that 3D tasks completed in a multi-user computer-aided design environment can improve the awareness of partners and increase communication frequency. Moreover, Gu et al. (2011) found that "3D virtual worlds sufficiently support design collaboration with designers remotely located and without major compromises for the quality of design communication and representation" (p. 274). This indicates that synchronous manipulation facilitates effective interactions among team members, enhancing communication during 3D design tasks.

Other research suggest that it can be challenging to communicate spatial information during 3D work. Hong et al. (2019) compare the use of a 3D representation with a 2D representation for online sketching, finding that the virtual 3D environment allow the participants to communicate spatial information more directly and effectively to their partners, such as moving the 3D representations around. In this context, synchronous manipulation enables collaborators to convey spatial concepts better and facilitate understanding among team members. Despite the positive effects, there are some negative effects of synchronous manipulation detected. For example, too much time is spent on coordination in the 3D virtual worlds (Deng et al., 2022; Gu et al., 2011). This suggests that synchronous manipulation enhances communication and collaboration, it may also require effective management and coordination to ensure optimal efficiency during virtual collaborative work.

In shared 3D design environments where all individuals have the ability to directly contribute during collaborations, individuals can use a mix of independent and interactive work modes within the same task session. Gu et al. (2011) discovered that individuals tend to work more independently under remote conditions than in co-located conditions. This means users are free to choose to work together or independently. A shared workplace is created in the 3D environment allowing more flexible designer activities. In comparison to a co-located sketch environment, multi-user synchronous sketch sessions in virtual 3D design environments "have the benefit of a smoother transition between working on the same group task and working on separate individual tasks pertaining to one project" (Gu et al., 2011, p. 277). Moreover, according to Stone et al. (2017), high-performing teams tend to communicate less with teammates while contributing more to the group task by manipulating the 3D software/platform. Hence, synchronous manipulation of the 3D design tools is essential in those contexts.

There have been mixed findings regarding synchronous manipulation and 3D design task performance. Eves (2018) concluded that a multi-user 3D environment can help increase task performance compared to a single user. Phadnis et al. (2021) found that groups working without synchronous manipulation can create higher-quality 3D models than those in synchronous manipulation mode because one of the two users is constantly checking while the other one is manipulating. However, groups in the parallel mode with synchronous manipulation, working with multiple users' input, complete tasks faster. On the other hand, Deng et al. (2022) investigated a

3D robotic task competition completed by large teams, concluding that synchronous real-time collaboration does not improve task performance. This is due to the distractions and coordination challenges caused by synchronous manipulation activities within a large team.

Studies by Piegl (2005) and Cheng et al. (2023) have presented the challenges associated with distributed computer-aided design work, underscoring the multi-decade need to address users' expectations for support of real-time updates and synchronous editing of 2D and 3D models. With the development of cloud technology, some researchers (e.g., Bidarra et al., 2003; Du et al., 2016; French et al., 2015; Song et al., 2015; Wu et al., 2017) have emphasized the advantages of synchronous manipulation, enabling real-time simultaneous multi-user computer-aided-design and offering technical solutions to support synchronous manipulation in a multi-user 3D design tasks. Despite these efforts, a thorough discussion on the impacts of a collaboration environment with and without synchronous manipulation on UX and collaboration outcomes has been lacking in their articles.

2.1.3 Synchronous Manipulation in Virtual Collaborative 3D Design Tasks on IWBs

IWBs have demonstrated positive impacts on collaboration processes and outcomes, as evidenced by a systematic review conducted by Mateescu et al. (2021). In a study by Schipper and Yocum (2016), users, including students and faculty, shared their experience with IWBs, and all participants reported positive attitudes, such as higher levels of satisfaction. Overall, previous studies have found that IWBs provide easier access to drawing, dragging, and moving objects, for group members to engage in collaborations at low communication costs.

Synchronous collaborations on general tasks using IWBs have been extensively studied and yield some benefits. However, much of the existing research has been limited to face-to-face contexts or focused on general tasks, with little exploration of their potential in other areas, such as 3D tasks. As a result, co-located collaborations on IWBs have garnered more attention and have been the subject of numerous studies that showcase their advantages. For example, Buisine et al. (2012) investigated face-to-face 2D brainstorming on an interactive tabletop and found that the device enhanced the participant experiences, making it more fun, pleasant, motivating, and attractive.

IWBs also promote collaboration equality and improved overall task performance. Rogers et al. (2009) demonstrated the feasibility of promoting group participation equality through a sharable interface on the tabletop during co-located collaborations. In a related study, Valérie et al. (2021) developed a co-located 2D game to explore the importance of balancing shareability and interdependence among teammates. Chen et al. (2021) highlighted the importance of "allowing users to freely choose whether to share or not to share the view/control of their workspace during the collaboration process" (p. 22). They also provide recommendations for completing visual exploratory tasks as paired groups in co-located learning settings with large interactive displays because it results in better task performance, efficiency, and higher engagement.

Research regarding virtual collaborations on IWBs has yielded some valuable insights. For instance, Siemon et al. (2017) have investigated how digital whiteboards can support team members in building shared mental models. The experiment reveals that the usage of an IWB positively impacts team interaction, satisfaction, shared understanding, and, ultimately, team performance. Zillner et al. (2014) studied synchronous manipulation during virtual collaborative 2D interior design and remote sketching on IWBs. They projected a figure on screen through software called 3D-board to allow one to see the teammate's location and manipulations simultaneously. It revealed that the 3D-board significantly improves the effectiveness of remote collaboration on IWBs, and significantly less frustration, less effort, and better performance were found.

In terms of 3D collaborations completed on IWBs, limited research has focused on co-located collaboration. One study from Kubicki et al. (2019) examined 3D design-related work (face-to-face 3D design coordination meetings) by comparing conditions using a video projector combined with a laptop PC to conditions using an IWB. They found that IWBs encourage more interactions and engagement among team members. IWBs were found to enable a deeper review of issues in the 3D virtual space and foster better team engagement. However, a video projector was found to be more efficient for solving simple problems.

To optimize the utilization of IWBs, it becomes imperative to understand the impact of synchronous manipulation on the collaboration process and outcomes. One related research by Phadnis et al. (2021) compares 3D modeling in a 3D environment with and without synchronous manipulation on computers. It concludes that there is no significant difference in satisfaction, but significant differences were found in the task completion time and the quality of the collaboration outcomes. Building upon the findings of Phadnis et al. (2021), our research focuses on expanding their results to IWBs.

On the other hand, regarding shared-screen studies, early research on synchronous collaborative computer-aided design by Mishra et al. (1997) discussed the sharing functionality of general design tools, which support remote design collaboration. Phadnis et al. (2021) mention that the shared-input mode without synchronous manipulation offers less freedom for the user, but it benefits the quality of the 3D design outcome. Nevertheless, the other relevant studies regarding collaborative tasks completed via shared screens have found a mixed effect. Thomas et al. (2023) examine how professionals' perceptions of video conferencing apps influence their use and continued use in a professional context. They point out that video conferencing can improve media synchronicity, which results in professionals fostering a higher sense of usefulness of video conferencing apps for tasks and higher performance expectancy. However, intense concentration requires more interactions and coordination, such as group decision-making and negotiation, which can increase the users' cognitive load.

Giving the findings and gaps, we propose our first research question. Specifically, we examine how does synchronous manipulation on an interactive whiteboard influences user experience, contribution, and performance during virtual 3D design work.

2.2 Individual Spatial Ability

2.2.1 Introduction

Individual spatial ability is defined as "the ability to generate, retain, and transform abstract visual images" (Lohman, 1979, p. 3). Spatial ability is a crucial predictor of performance in spatial tasks that demand high spatial visualization and mental animation abilities (Carroll, 1993; Hegarty & Waller, 2005). Spatial ability has been shown to influence job performance in occupations such as engineering drawing, drafting, and designing (Hegarty & Waller, 2005).

Individual possess varying levels of spatial ability, so they exhibit different processing speeds and employ diverse strategies when dealing with spatial information (Mohler, 2008). Consequently, spatial ability can affect people's performance during 3D tasks like 3D drawing and 3D modeling. Moreover, individuals with high spatial ability tend to get better scores. For example, when completing a creative 3D model of a multi-purpose pen holder in a 3D design software, Chang (2014) found that high spatial ability students performed better; Similarly, Barrera et al. (2019) studied 3D drawing in a 3D virtual environment, revealing that high-spatial-ability users achieve a better score than low-spatial-ability-users, due to their enhanced spatial orientation ability.

2.2.2 Spatial Task Performance and Experience in 3D Design Environments

Existing research has demonstrated the effectiveness of spatial training in 3D design environments in improving individual spatial task performance and experience. Lee and Ostwald (2022) conducted a comprehensive review of digital platforms and concluded that 3D sketching interfaces can improve spatial cognition. Rafi et al. (2005) found that spatial ability can be improved by training in a virtual environment called WbVE. Students received higher post-training scores on visualization and mental rotation tests. The results have shown that WbVE is more effective in developing a subject's basic spatial strategies to deal with spatial tasks than traditional classroom practices. Rafi et al. explain as learns' "understandings were further enhanced by simulations of the object depicting appropriate views […] through practice in WbVE the subjects may have developed the cognitive strategy to solve mental rotation tasks" (2005, p. 712).

Further reinforcing these findings, Rafi and Samsudin (2009) demonstrate that an interactive desktop mental rotation trainer (iDeMRT) can improve mental rotation ability. This platform facilitated improvements in mental rotation skills, thereby enhancing spatial abilities. Another noteworthy study by Šafhalter et al. (2022) focused on training children under 14 in a 3D modeling course. After training, spatial visualization ability was improved, and the students got higher scores on spatial tests such as Mental Rotation Test (MRT) and Purdue Spatial Visualization Test. Additionally, Roca-González et al. (2016) tested virtual reality (VR) and augmented reality (AR) engineering training activities aiming at improving components of spatial ability, including mental rotation, spatial visualization, and spatial orientation.

The impacts of 3D spatial ability training can vary depending on an individual's baseline spatial ability level. Researchers have observed that individuals with high and low spatial ability experience different degrees of benefit from such training. For example, Froese et al. (2013) studied using external representations to improve spatial ability and found that visualization training programs effectively enhanced 3D task performance. Interestingly, the researchers noted that these training programs were more beneficial for individuals with low spatial ability than those with high spatial ability. Training individuals with high spatial ability using dynamic visualizations provided little additional benefit. Supporting these findings, a recent study by Piri and Cagiltay (2023) conducted a systematic review that emphasized the role of 3D visualization tools in enhancing mental rotation ability. They found that individuals with low spatial ability levels benefit more from 3D visualization tools than those with high spatial ability levels.

Positive effects have been observed regarding the impact of spatial ability on individual experience while performing a 3D task in a 3D design environment. According to the findings of Dere and Kalelioglu (2020), the web-based 3D design environment (Tinkercad) has been shown to improve the spatial ability of individuals. The students who participated in their study reported that spatial ability tests became more effortless after using Tinkercad. This improvement is attributed to the platform’s ability to let users look at objects from different angles. The students felt the 3D platform (Tinkercad) is entertaining, enjoyable, and practical for resolving spatial problems in a 3D environment rather than in their minds. Tinkercad is perceived as useful and helpful for completing a spatial task, and using a web-based 3D design environment significantly increases all spatial ability test results, especially for low spatial ability student.

Other research discussed the impact of low and high spatial ability during 3D tasks. The participants requested control over 3D objects in a study conducted by Froese et al. (2013), so the users could rotate the object, alter the orientation, and control the speed of the animation. Nevertheless, the authors argue that user control “might increase the cognitive load on the user and could be detrimental to individuals with LA [low spatial ability]. For individuals with HA [high spatial ability], a more user controlled interaction would be more engaging but perhaps would still not benefit performance” (Froese et al., 2013, p. 2816).

During their research on co-located 3D collaboration, Stone et al. (2017) identified spatial manipulation ability as a crucial factor influencing team performance in 3D modeling tasks, along with providing a multi-user computer-aided design environment. Our research about enhancing 3D task performance and experience through appropriate tools could be a valuable approach to improving 3D collaboration. In addition, a research gap is mentioned by Hegarty & Waller (2005) regarding how individual spatial information processing abilities influence complex cognition task performance. To address this gap, our research investigates our second research question: how the effects of synchronous manipulation on a 3D design task are moderated by an individual's spatial ability.

Chapter 3: Hypothesis Development

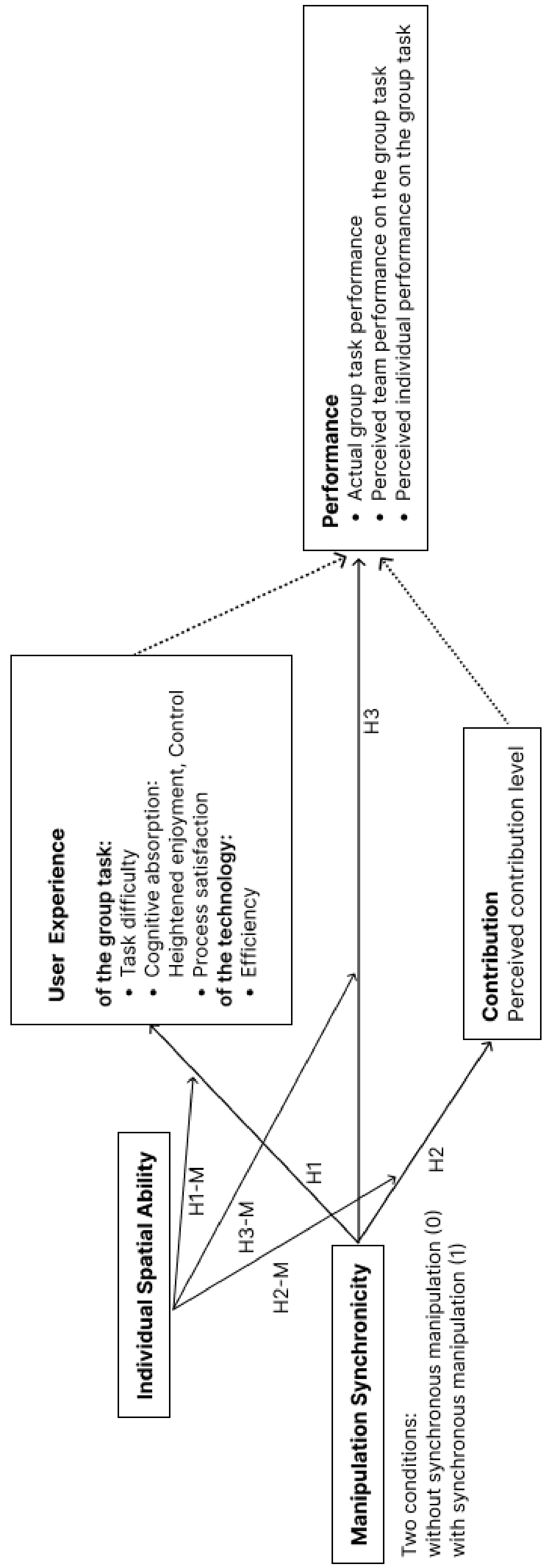
In this chapter, we present our research model. We also propose and justify the hypotheses related to our research questions, specifically investigating how synchronous manipulation and individual spatial ability impact UX, contribution, and task performance during virtual collaborative 3D design tasks on IWBs.

3.1 Proposed Research Model and Variables

To address our research questions, we analyzed the existing studies regarding synchronous virtual collaboration on IWBs and individual spatial ability impacts on UX, contribution, and performance during 3D design tasks. Based on the relevant findings, we created a research model and came up with hypotheses.

Specifically, for the various components of UX, five hypotheses were proposed, denoted as H1a, H1b, H1c, H1d, and H1e. One, H2, was developed to examine the impact on individual contribution. Three hypotheses, labeled H3a, H3b, and H3c, were created to investigate task performance. Furthermore, to understand the moderation effects of individual spatial ability, nine hypotheses which correspond to a moderation effect on the nine direct relationships proposed above were labeled as H1a-M, H1b-M, H1c-M, H1d-M, H1e-M, H2-M, H3a-M, H3b-M, and H3c-M. The research model outlining these hypotheses is presented in **Figure 1**.

Figure 1 *Research Model*



3.2 Proposed Hypotheses

3.2.1 Influence of Manipulation Synchronicity on User Experience

As part of our first research question, we want to examine how synchronous manipulation on an IWB influences UX during virtual 3D design work. There are multiple aspects of UX that may be relevant, such as perceived task difficulty, cognitive absorption, process satisfaction, and efficiency.

Synchronous manipulation in a 3D environment may be a factor influencing perceived task difficulty. We believe that the use of 3D platform manipulation will reduce perceived task difficulty for collaborative 3D design tasks. Task difficulty is “the extent to which the performer describes his or her current task as novel, complex, and difficult” (Fisher & Noble, 2004, p. 149). Task difficulty is associated with effort, and “more difficult tasks should call forth more effort because more effort is seen as required to succeed on such tasks” (Fisher & Noble, 2004, p. 149). During the collaboration, when participants can manipulate the object and rotate it to look at it and work on it from different angles, this allows them to communicate more efficiently during the task, requiring less explanation. All participants can work more directly with the objects. When only one participant can manipulate the object, more effort is needed to correctly communicate the placement and rotation of certain objects, as the other participants are interacting indirectly with the object, requiring more communication effort. Thus:

H1a: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will perceive lower task difficulty than those collaborating without synchronous manipulation.

Synchronous manipulation may be a factor influencing cognitive absorption, defined as "a state of deep involvement with software" (Agarwal & Karahanna, 2000, p. 673). It consists of five dimensions: temporal dissociation, focused immersion, heightened enjoyment, control, and curiosity. We are interested in heightened enjoyment and control of interactions during spatial tasks. We believe that the use of synchronous manipulation will increase cognitive absorption during the collaborative 3D design task. This is because interacting with IWBs is motivating and engaging (Buisine et al., 2012; Kubicki et al., 2019; Mariz et al., 2017; Mateescu et al., 2021; Valérie Maquil et al., 2021). A 3D design environment is immersive, fun, and enjoyable when users can manipulate within those environments (Dere & Kalelioglu, 2020; Gu et al., 2011; Hong et al., 2016). Furthermore, synchronous manipulation makes the collaboration process more enjoyable because this collaboration mode makes it easier to communicate information (Mabrito, 2006; Rahman et al., 2013a). Gu et al. (2011) found that 3D design environments allow for the flexible switch between independent work and co-work. In terms of control, under synchronous manipulation conditions, all members are able to manipulate objects on the IWBs, while those collaborating without synchronous manipulation who do not have editing access would feel like they have less control over the work.

H1b: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will perceive more enjoyment than those collaborating without synchronous manipulation.

H1c: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will perceive more control than those collaborating without synchronous manipulation.

Synchronous manipulation may be a factor influencing process satisfaction with the collaboration. Previous research by Dere and Kalelioglu (2020) found that students were satisfied with being able to create something with practical tools like Tinkercad. However, they do not examine satisfaction with the collaboration process or the spatial design tasks. Users perceive the process as satisfying when they are happy with the information and technology efficacy during the task (Lowry et al., 2009). For those collaborating with synchronous manipulation, users could make full use of the tools to communicate and complete the task, which should increase their satisfaction. Thus,

H1d: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will perceive higher collaboration process satisfaction than those without synchronous manipulation.

Synchronous manipulation may be a factor influencing the perceived efficiency of the technology. We believe that collaborating with synchronous manipulation will positively influence the perceived efficiency of the technology used during collaborative 3D design tasks for several reasons. First, more effective interactions can take place by having all users within the group being able to rotate objects. In this sense, Dere and Kalelioglu (2020) found that using a web-based 3D design environment helps individuals with lower spatial abilities more than when without such environment, they have to imagine such objects as well as their spatial manipulations, thus, making them as well more satisfied with the 3D design environment. Second, synchronous manipulation can result in more efficiency, since past research suggests it can help mitigate the challenge of conveying and communicating spatial information. In support of this, Hong et al. (2019) found that, during synchronous sketching, 3D representations helped communicate spatial information directly and efficiently among collaborators. Finally, past research has also shown that groups employing synchronous manipulation with a 3D design were able to complete more tasks within a limited time than those without synchronous manipulation, thus, increasing the efficiency for the synchronous groups ((Phadnis et al., 2021). Thus, the use of technology with synchronous manipulation should increase the perceived efficiency of the technology.

H1e: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will perceive the technology as more efficient than those without synchronous manipulation.

3.2.2 Influence of Manipulation Synchronicity on Contribution

Synchronous manipulation may influence a user's perceived individual contribution during group tasks. Gül and Maher (2009) found that a shared working space impacts how designers contribute. When 3D modeling, individuals initially spend most of the time on their own parts, then collaborate with the other members afterward. On the other hand, Valérie et al. (2021) pointed out that in a co-located context, only one member being able to manipulate content promotes a joint focus but also collaboration inequality. We believe that when collaborating with synchronous manipulation, all members could work on the design task simultaneously and would perceive that they are contributing to the work. However, without synchronous manipulation, the non-controlling partner may perceive themselves as making a lower contribution due to their inability to edit the objects. Thus, using technology with synchronous object manipulation should increase perceived contribution during collaborative 3D design tasks. Hence:

H2: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will feel that they contribute more than those without synchronous manipulation.

3.2.3 Influence of Manipulation Synchronicity on Task Performance

Synchronous manipulation may also influence task performance. Previous research has found that the use of IWBs has positive effects on collaborative task performance in multiple contexts, such as education (Clayphan. et al., 2016; Shi et al., 2019) and the workplace (Lee et al., 2015; Mateescu et al., 2021; Renger et al., 2008). In addition, for collaborative 2D design tasks, synchronous manipulation can help improve task performance (Rahman et al., 2013; Yim et al., 2017).

For 3D design-related tasks, some mixed effects were also detected by previous studies (e.g., Deng et al., 2022; Phadnis et al., 2021). Synchronous manipulation will positively influence team performance for collaborative 3D design tasks. This is because negative effects were detected by Deng et al. (2022) in a large-scale collaboration context where users became distracted when too many people manipulated objects at the same time. In our research, there are fewer team members, which may mitigate the potential distractions. Additionally, the 3D modeling task in the experiment of Phadnis et al. (2021) is to focus on the same 3D object simultaneously, such as a cup. In contrast, our research explores more flexible group tasks allowing participants to contribute to different parts of the project. They can communicate and operate well with partners, leading to better task performance. Thus, synchronous manipulation should improve task performance for collaborative 3D design tasks. We propose:

H3a: Individuals collaborating on an IWB with synchronous manipulation during virtual 3D design task will have better actual group task performance than those without synchronous manipulation.

H3b: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will perceive better team performance on the group task than those without synchronous manipulation.

H3c: Individuals collaborating on an IWB with synchronous manipulation during a virtual 3D design task will perceive that their own individual performance on the group task is better those without synchronous manipulation.

3.2.4 Moderating Influence of Individual Spatial Ability

Our second research question examines how these effects are moderated by an individual's spatial ability. Previous studies found that external visualization support and virtual technology training can help improve spatial task performance and individual experience on spatial tasks (Cohen & Hegarty, 2007; Froese et al., 2013). For instance, Dere and Kalelioglu (2020) found that a 3D design environment, Tinkercad, can help improve spatial abilities as it helps improve visualization and mental rotation. The students also perceived the spatial test questions easier after training. Lee and Ostwald (2022) also found that digital design platforms enhance spatial design cognition.

Research has found that low spatial ability individual reacts differently than high spatial ability individuals. Froese et al. (2013) and Dere and Kalelioglu (2020) found that spatial training programs/3D design platforms were more beneficial for individuals with low spatial ability than individuals with high spatial ability. Based on spatial ability research by Hegarty and Waller (2005), we can infer that for high spatial ability users who are already proficient at rotating and visualizing 3D objects in their mind, synchronous manipulation would not be as impactful as for low spatial ability users. For users with low spatial ability, their spatial information processing speed and strategies are weaker and synchronous manipulation could aid and enhance their ability to understand and manipulate objects in a 3D context. Thus, we believe that individuals' spatial ability will moderate the relation between manipulation synchronicity on a 3D collaborative design task (with vs. without synchronous manipulation) and perceived UX, perceived contribution level, and task performance. The relationships will be weaker for high spatial ability users than for low spatial ability users, such that:

H1a-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and task difficulty, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and task difficulty will be weaker than for individuals with low spatial ability.

H1b-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and perceived enjoyment, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and enjoyment will be weaker than for individuals with low spatial ability.

H1c-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and perceived control, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and perceived control will be weaker than for individuals with low spatial ability.

H1d-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and perceived process satisfaction, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and process satisfaction will be weaker than for individuals with low spatial ability.

H1e-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and perceived efficiency, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and perceived efficiency will be weaker than for individuals with low spatial ability.

H2-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and perceived contribution, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and perceived contribution will be weaker than for individuals with low spatial ability.

H3a-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and actual group task performance, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and real performance will be weaker than for individuals with low spatial ability.

H3b-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and perceived team performance on the group task, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and perceived team performance on group task will be weaker than for individuals with low spatial ability.

H3c-M: An individual's spatial ability will moderate the relationship between synchronous manipulation and perceived individual performance on the group task, such that for individuals with higher spatial ability, the relationship between synchronous manipulation and perceived individual performance on group task will be weaker than for individuals with low spatial ability.

Chapter 4: Methodology

This chapter presents the methodology adopted for conducting this research, including a laboratory experiment, a standard spatial ability test, and the implementation of two questionnaires to facilitate data collection. The presentation of the experiment encompasses comprehensive descriptions of the participants, the experimental procedure, and the measurement of constructs.

4.1 Experimental Design Overview

We used a laboratory experiment accompanied by questionnaires for this research. These approaches increase the reliability and validity of data collection, as it is easier to control experimental conditions in a laboratory context. The 2-person group 3D design task outcomes were used to analyze the effects of synchronous manipulation on actual group task performance. The experiment's objective is to analyze the collaborations during 3D design tasks on IWBs. An experimental approach also helps us to infer causal relationships between the independent variable (manipulation synchronicity) and dependent variables (UX, perceived contribution level, perceived team and individual performance on a group task, and actual group task performance) and predict the moderation effects of individual spatial ability.

The 3D design task took place on two IWBs located in two separate study rooms. Each study room had a large display and an IWB hanging on parallel to the same wall. All groups used video conferencing software, Zoom, for real-time video communication. The video was displayed on a second non-interactive monitor. All groups used a web-based real-time 3D design platform, Tinkercad (https://www.tinkercad.com/), for the group 3D design task. The platform was opened via Chrome on IWB in each study room. All participants with manipulation access to Tinkercad could use their hands or a stylus on the IWB to manipulate the 3D objects on Tinkercad.

This experiment included two conditions (group 1 and group 2). Group 1 was without synchronous manipulation, and group 2 was with synchronous manipulation. For each experiment session for group 1, one of the two participants located in study room 1 plays the role called individual-control, having manipulation access to Tinkercad while his/her partner who is in study room 2 plays a role called guest joining the group design task by Zoom's share-screen that was displayed on the IWB. For each experiment session for group 2, both team members play the role of shared-control having the same synchronous manipulation access to Tinkercad on the IWBs in each study room.

The group 3D design task is to develop a layout proposal for a fictitious community named the Joly Community by planning and manipulating 3D infrastructure based on a pre-designed city map on Tinkercad. All instructions and design requirements were introduced to participants orally by a moderator and via a printed participant instruction document (see Appendix B).

4.2 Participants

We recruited 82 participants but dropped the data of six participants because of technical and attendance issues. The sample size is, therefore, 76 participants, and the characteristics are shown in **Table 2**. Each group was randomly assigned to only one of the experimental conditions (with synchronous manipulation vs. the control group without synchronous manipulation). Thus, our final analysis involves 76 participants who formed 38 groups, 19 in each condition.

Participants included 31 males and 45 females. Of these, 49.3% were 18-25 years old, 30.7% were 29-30, and the rest were over 30. Over 45% were completing their Master's studies, 25% were completing their bachelor's, and 10.5 % were completing their Ph.D. We recruited participants from an HEC Montréal research and recruitment panel. Among the participants, 55.2% were studying Business or finance-related programs, 23.7% were in IT, and 21.1 % were from other disciplines. Participants had a range of experience with 3D modeling tools (see **Table 3**), with the average experience level being relatively low. The participants' previous experience with Tinkercad is low and with very little variation (M=1.03, SD= 0.16).

Table 2 *Sample Demographic Statistics*

Baseline characteristic	Frequency	Percent
Gender (N=76)		
Male	31	40.8
Female	45	59.2
Age (N=76)		
18 to 25 years old	37	49.3
26 to 30 years old	23	30.7
31 to 35 years old	8	10.7
36 to 40 years old	4	5.3
41 to 45 years old	3	4
Not indicate	1	1.3
Education (N=76)		
Bachelor’s	19	25
Certificate	5	6.6
DESS	2	2.6
Master’s	36	47.4
Ph.D.	8	10.5
Other	6	7.9
Specialization (N=76)		
Finance	9	11.8
Information Technology (User Experience, Philosophy of AI, Data Science, Statistics, and Computer science)	18	23.7
Marketing	7	9.2
Management (Sustainable Development, Management in cultural organization)	5	6.6
Human Resources	1	1.3
Business Intelligence (International Business)	5	6.6
Accounting	6	7.9
Logistic (Supply Chain)	8	10.5
Project Management	1	1.3
Other (Arts/Literature, Medicine, Health, Biochemistry, Psychology, Industrial Engineering, Engineering, Translation, Education, Biological Science, Acting, Nursing, None)	16	21.1

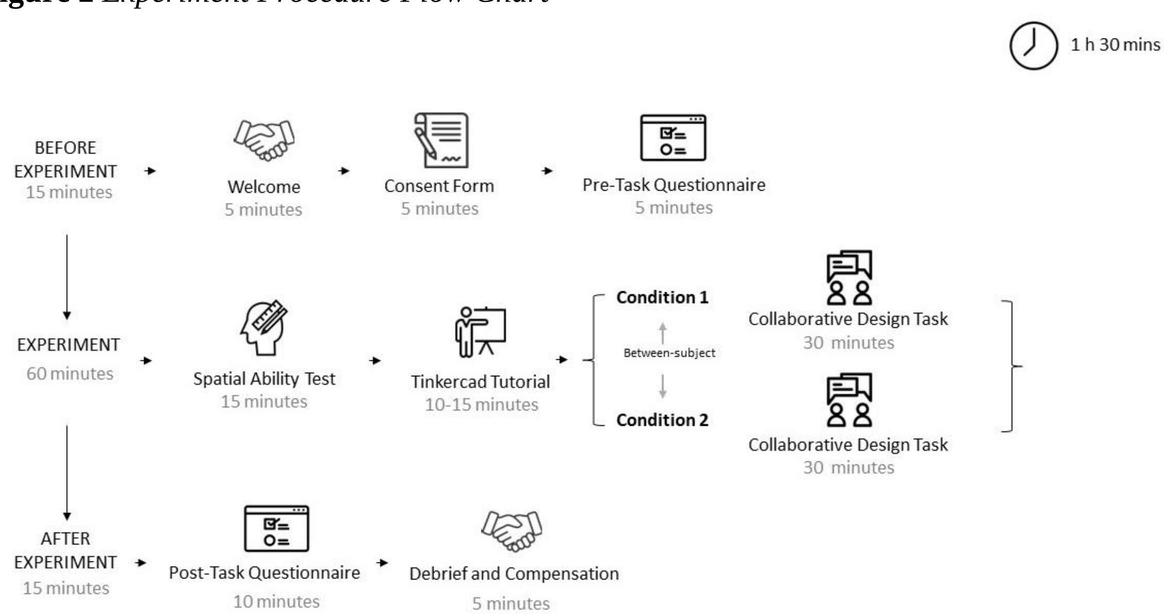
Table 3 *Previous 3D Platform Experience Descriptive Statistics*

	N	Minimum	Maximum	Mean	SD
AutoCAD	76	1	7	1.49	1.26
Solidworks	76	1	7	1.55	1.35
Autodesk Inventor	75	1	7	1.12	0.72
SolidEdge	76	1	2	1.04	0.20
Google Sketchup	76	1	5	1.32	0.80
Tinkercad	76	1	2	1.03	0.16
IKEA Planner	76	1	5	1.61	1.08
Lego Designer	76	1	5	1.28	0.79

4.3 Experiment Procedure

The whole experiment procedure (see **Figure 2**) lasted for 1.5 hours, including a short pre-task questionnaire with background questions, 15 minutes for the spatial ability test, 15 minutes for the Tinkercad tutorial so that participants would be well prepared for the 3D design platform, 30 minutes for the collaborative group design task, and finally, a 15-minute post-task questionnaire. The group task was to complete a community layout design in a 3D context. The group's performance on the 3D task was evaluated after the experiment by a grading scheme established in advance.

Figure 2 *Experiment Procedure Flow Chart*



4.3.1 Overview of Pre-Task Activities

At the beginning of each session, the two participants were invited to sit in two separate study rooms. One moderator from the lab gave them oral instructions on the experimental procedures and test objectives. They were then invited to sign a consent form approved by the HEC Montréal research ethics board and to complete a short background questionnaire that included questions on demographic information and previous 3D software /platform experience.

4.3.2 3D Design Platform (Tinkercad) Training

Tinkercad training was given in the study room separately for each participant. The training sessions aimed to ensure participants were familiar with the platform to the same extent. The training took an average of 15 minutes and included getting to know the interface, manipulating the map to change views, and adding and moving 3D objects in the 3D environment.

4.3.3 Group Task

Before the group task, participants read instructions for the group design task, which required designing the placement of buildings on a 3D “Joly Community” map. All group members were placed in separate rooms and could communicate through videoconferencing via a Zoom meeting. The researcher briefly emphasized the participants’ roles in the task (i.e., in the groups with synchronous manipulation, both members could manipulate the Tinkercad project, while in the controlled group without synchronous manipulation, only one team member could manipulate the Tinkercad project, while the other could only see the project via a shared screen in the Zoom meeting.) The researcher presented the Joly Community map and showed them how to solve emergency technical issues. Each group had 30 minutes to complete their task.

This 3D design task required spatial abilities to manipulate the 3D objects, including visualization (the planning stage required visualizing where to build structures before adding them to the map) and rotation (rotating buildings while changing a building’s position to meet requirements). In addition, this group task required discussion to interpret the instructions and plan an approach and math calculations to meet the task requirements. The instructions for each participant include four sections: collaboration guidelines, task guidelines, project mandate, and detailed requirements (see

Appendix B). Collaboration guidelines and task guidelines sections vary slightly according to the participant's role in each group. The project mandate and detailed requirements sections for the two conditions are the same.

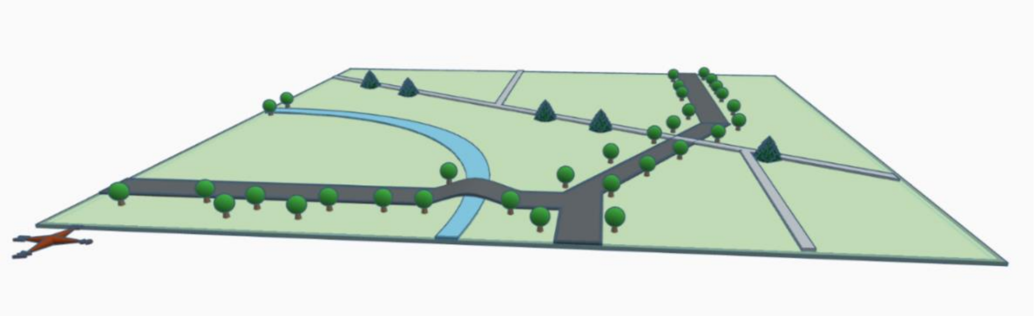
The task was a spatial planning exercise in which the teams proposed a development plan for the Joly Community. The existing map consisted of roads, trees, and rivers (see **Figure 3**). It is forbidden to change the basic map. The development proposal needed to meet the following criteria:

1) Include appropriate numbers of residential buildings (houses and apartments) to fit 200 residents, including 50 children.

2) 120 residents live in houses. 80 live in apartments.

3) Include a fire station, a police station, a medical clinic, a school, a shopping center, and a sports center to ensure comfortable living.

Figure 3 *The Joly Community Map*



There were also other constraints for the choice and placement of the buildings. For example, for a house:

1) Each house can fit six residents maximum.
2) Houses in the final proposal must fit 120 Joly Community residents in total.
3) The front door of a house must face a road.
4) Houses cannot be beside the river.

Participants had to discuss with teammates and adjust building locations to meet all requirements. Some requirements also require creating multi-floor buildings floor-by-floor, by moving and rotating each floor to align them properly with each other. For example, building apartments. One possible proposal is shown in **Figure 4**.

Figure 4 *One Possible Proposal for the Joly Community Layout*

4.4 Measures

Data was successfully collected for 38 experiment sessions. The resulting 38 community layout design proposals were saved on the Tinkercad server, and the proposals were graded by the researcher after the experiment. Participants were also asked to fill out both pre-task and post-task questionnaires about their experience with the technology used, the design task, and collaboration. Four constructs in the research model were measured: individual spatial ability, perceived UX, perceived individual contribution, and task performance.

Individual spatial ability was measured by a standard MRT (Peters et al., 1995). The test was developed by Peters and colleagues based on a reliable test initially created by Vandenberg and Kuse (1978) and is now widely used for measuring mental rotation (Dere & Kalelioglu, 2020; Hegarty et al., 2006; Rafi & Samsudin, 2009; Šafhalter et al., 2022), which is the aspect of the spatial ability required by our 3D group task. Each test session took 5-8 minutes for introduction and practice exercises. The 8-minute formal test consisted of 24 spatial rotation questions. and participants received 1 point for one question correctly answered.

Self-reported quantitative measures were assessed by a post-test questionnaire. All the self-reported measures used are presented in Appendix C. UX was measured by task difficulty (Fisher & Noble, 2004), process satisfaction (Lowry et al., 2009), and cognitive absorption (including heightened enjoyment and control) (Agarwal & Karahanna, 2000). The subjective experience of technology set-up was measured by user experience questionnaire (UEQ) - efficiency (Schrepp et al., 2017). A newly developed scale, contribution level, measured the perceived individual contribution The perceived group task performance was measured by task performance items from Fisher and Noble (2004). Participants were asked to rate each item in the questionnaire on a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree).

For all the factors used in our research model, we ran reliability tests, including Cronbach's alpha (α) analysis and Exploratory Factor Analysis (EFA). After dropping some items due to reliability and EFA issues (see Appendix D) we reran the reliability tests with satisfactory results (see **Table 4**, **Table 5**, and **Table 6**). Please note that all labels of the constructs in **Table 6** are presented in Appendix C.

Table 4 *Cronbach's Alpha (α) Results of All Measures*

Constructs		M	SD	Cronbach's Alpha (α)
Task difficulty		3.71	1.46	.731
Cognitive absorption	Heightened enjoyment	5.87	.894	.894
	Control	5.03	.633	.633
Process satisfaction		5.51	1.16	.820
Efficiency		5.17	1.22	.823
Perceived contribution level		6.35	.93	.881
Perceived team performance on group task		5.43	1.17	.921
Perceived individual performance on group task		5.37	1.12	.899

Table 5 *Exploratory Factor Analysis (EFA) Results*

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.833
Bartlett's Test of Sphericity	Approx. Chi-Square	1581.141
	df	351
	Sig.	<.001

Note: df = Degree of Freedom; Sig. = Significance

Table 6 *Rotated Component Matrix*[a] *of All Measures*

	Component						
	1	2	3	4	5	6	7
Tsk_Perfm_TeamX	.835						
Tsk_Perfm_Team3	.826						
Tsk_Perfm_Team1	.797						
Tsk_Perfm_IndvX	.782						
Tsk_Perfm_Indv1	.765						
Tsk_Perfm_Indv3	.755						
Tsk_Perfm_Team2	.638						
Tsk_Perfm_Indv2	.543	.506					
Contr_level1		.770					
Contr_level2		.719					
HE1		.714				.409	
HE2		.711					
HE3		.692					
Process1	.420		.790				
Process3_r			-.737				
Process4			.684				
Process5			.651				
Effi2				.810			

	Component						
	1	2	3	4	5	6	7
Effi3				.798			
Effi1				.636			
Effi4				.617		.459	
CO1					.777		
CO2_r					-.719		
Process2_r					-.519	-.501	
HE4_r						-.776	
Diff2							.866
Diff1							.862

Note: a. Rotation converged in 8 iterations.

Actual group task performance was measured using the pre-established grading criteria (see Appendix E). We assessed task outcomes from three activity types: building number calculations (rules 1, 7, 9), adding the required building types (rules 7, 9, 12, 14, 16, 18, 20, 22), and adjusting to suitable building locations and alignments (rules 2, 3, 4, 5, 6, 8, 10, 11, 13, 15, 17, 19, 21, 23). Each rule was assigned 1-5 points according to the complexity level with 41 points in total.

Chapter 5: Results

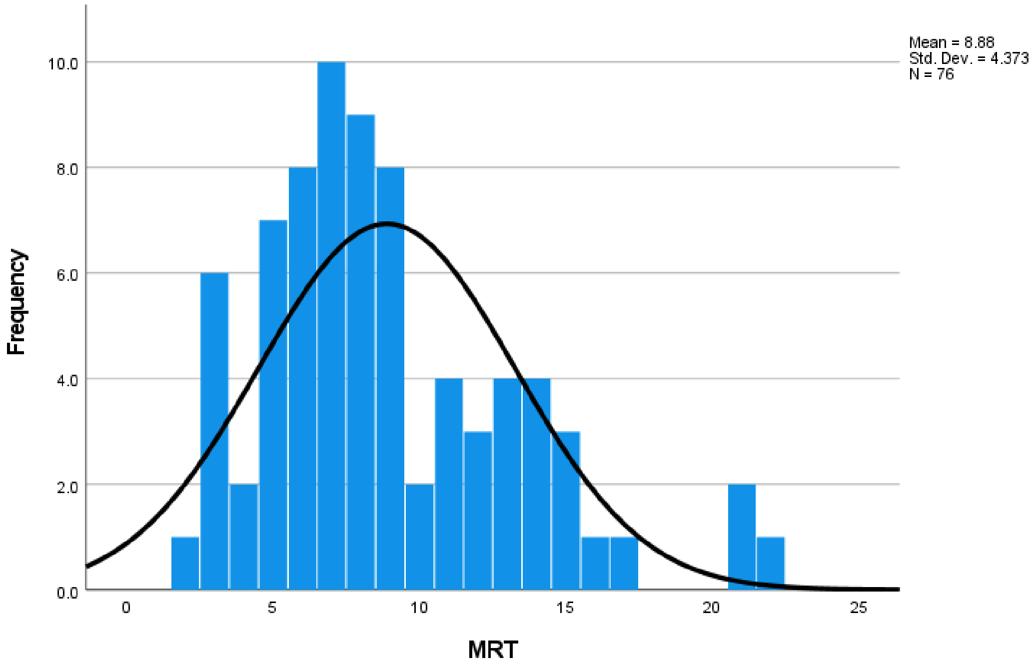
This chapter will present the data analysis process, including descriptive analysis, t-test results of two independent samples (two groups with and without synchronous manipulation), and individual spatial ability moderation analysis. We also present and summarize the data analysis results according to our study hypotheses. We used 76 data sets in total from 38 experiment sessions for data analysis.

There were two independent groups from two manipulation synchronicity conditions: group 1- without synchronous manipulation, and group 2- with synchronous manipulation. There are 38 data sets for each condition, and a t-test was run to compare the means of all dependent variables. Finally, moderation analysis with individual spatial ability were run with manipulation synchronicity as the independent variable. In addition, we ran another post-hoc moderation analysis with role (1-shared control; 2-individual control, 3-guest) as an independent variable, and all dependent variables were included, with individual spatial ability as the moderator. 76 cases were analyzed.

5.1 Descriptive Analysis

The MRT grade distribution (see **Figure 5**) is aligned with a normal distribution. There is no standard specifying which score corresponds to high spatial ability and low spatial ability participants. We use this sample to represent the population's spatial ability distribution.

Figure 5 *Sample Histogram of MRT Grades*



The descriptive statistics of all independent variables (see **Table 7**) show the means, maximums, minimums, and standard deviation values of all 76 participants. The participants rated each measure from 1 (strongly disagree) to 7 (strongly agree), and we treated the reversed measures.

Table 7 *Descriptive Statistics of Model Constructs*

Construct	N	Minimum	Maximum	M	SD
MRT	76	2	22	8.88	4.37
Task difficulty	76	1.00	7.00	3.71	1.46
Heightened enjoyment	76	1.50	7.00	5.87	1.08
Control	76	1.00	7.00	5.03	1.35
Efficiency	76	1.50	7.00	5.17	1.22
Process satisfaction	76	1.80	7.00	5.51	1.16
Perceived contribution level	76	2.00	7.00	6.35	.93
Perceived team performance on group task	76	2.00	7.00	5.43	1.17
Perceived individual performance on group task	76	1.00	7.00	5.37	1.12

5.2 Results of Independent Samples T-Test

An independent-samples t-test was conducted to determine whether there is a difference in each dependent variable between the two groups: without synchronous manipulation (group 1) and with synchronous manipulation (group 2). The null hypothesis posited that no difference existed; specifically, it suggested that the means of group 1 were equivalent to those of group 2 ($M_1 = M_2$). In contrast, the alternative hypothesis proposed a dissimilarity: the means of group 1 were not equal to that of group 2 ($M_1 \neq M_2$).

Overall, t-test results (see **Table 8**) show that comparing of the average scores of the participants without synchronous manipulation (group 1) to those with synchronous manipulation (group 2). Participants with synchronous manipulation rated heightened enjoyment, control, process satisfaction, perceived contribution level, and task performance significantly higher than those in without synchronous manipulation.

For H1a, our experiment does not indicate a significant difference between the groups with synchronous manipulation average (M_2 = 3.56, SD= 1.24) and the groups without synchronous manipulation average (M_1 = 3.87, SD= 1.66), 95% CI [-0.35, .99], (t (68.51) = 0.94, $p = 0.351 > 0.05$). Consequently, we fail to reject the null hypothesis that there is no difference between the sample means. Thus**, H1a is not supported.**

For H1b and H1c, the data shows that groups with synchronous manipulation perceived significantly more cognitive absorption than groups without synchronous manipulation. For heightened enjoyment, groups with synchronous manipulation average (M_2 = 6.19, SD= .67) is higher than groups without synchronous manipulation (M_1 = 5.55, SD= 1.31). At a 5% significance level, the difference between means, 95% CI [-1.12, -0.16], is significant (t (55.09) = -2.68, $p = 0.010 < 0.05$). For control over the technologies, the groups with synchronous manipulation average (M_2= 5.45, SD= .90) is higher than those without synchronous manipulation average (M_1= 4.61, SD= 1.59). The difference between means (95% CI [-1.44, -0.25]) is also significant (t (58.36) = -2.84, $p= 0.006 < 0.05$). Thus, **H1b and H1c are supported.**

For H1d, on average, groups with synchronous manipulation perceived a higher process satisfaction level ($M_2 = 5.79$, SD= .97) than groups without synchronous manipulation ($M_1 = 5.22$, SD= 1.27). This difference, with 95% CI [-1.09, -0.05], is statistically significant at a 5% significance level (t (74) = -2.20, $p = 0.031 < 0.05$). Thus, **H1d is supported.**

For H1e, on average, groups with synchronous manipulation did not perceive the technologies setting-up as more efficient ($M_2 = 5.42$, SD= 1.20) than groups without synchronous manipulation ($M_1 = 4.91$, SD= 1.20). However, at a 5% significance level, the difference with 95% CI [-1.05, .05] is non-significant (t (74) = -1.83, $p = 0.072$). Consequently, users in the two groups perceive the technology's efficiency differently at a 10% significance level. **Hence, hypothesis H1e can only be marginally supported.**

For H2, users in a tech setting with synchronous manipulation may believe they contribute more. On average, groups with synchronous manipulation ($M_2 = 6.58$, SD = .60) is higher than groups without synchronous manipulation ($M_1 = 6.12$, SD= 1.13). At a 5% significance level, the difference, with 95% CI [-0.88, -0.05], is significant (t (56.27) = -2.22, $p = 0.030 < 0.05$). **Thus, H2 is supported.**

For H3a regarding the actual group task performance, the average grade of groups with synchronous manipulation ($M_2 = 31.79$, SD= 6.72) is better than groups with synchronous manipulation ($M_1 = 25.11$, SD= 6.62). At a 5% significance level, this difference, with 95% CI [-9.73, -3.64], is significant (t (74) = -4.37, $p < 0.001$). Thus, **H3a is supported.**

For perceived team performance on the group task, on average, participants in groups with synchronous manipulation perceived better team task performance ($M_2 = 5.87$, SD= .94) than those in groups without synchronous manipulation ($M_1 = 5.00$, SD= 1.21). At a 5% significance level, this difference, with 95% CI [-1.37, -0.37], is significant (t (74) = -3.47, $p < 0.001$). For perceived individual performance on the group task, on average, participants in groups with synchronous manipulation perceived better individual performance on the group task ($M_2 = 5.72$, SD= 0.91) than those in groups with synchronous manipulation ($M_1 = 5.01$, SD= 1.21). At a 5% significance level, this difference, with 95% CI [-1.20, -0.21], is significant (t (74) = -2.86, $p = 0.006 < 0.05$). Thus, **H3b and H3c are supported.**

Table 8 *Independent Samples T-Test Results*

	Group 1		Group 2		t	df	p	95% Confidence Interval of the Difference	
	M	*SD*	*M*	*SD*				Lower	Upper
Diff	3.87	1.66	3.56	1.24	.94	68.51	.351	-.35	.99
HE	5.55	1.31	6.19	.67	-2.68	55.09	.010*	-1.12	-.16
CO	4.61	1.59	5.45	.90	-2.84	58.36	.006*	-1.44	-.25
Process	5.22	1.27	5.79	.97	-2.20	74	.031*	-1.09	-.05
Effi	4.91	1.20	5.42	1.20	-1.83	74	.072	-1.05	.05
Contr_level	6.12	1.13	6.58	.60	-2.22	56.27	.030*	-.88	-.05
Real Task Perf	25.11	6.62	31.79	6.72	-4.37	74	<.001*	-9.73	-3.64
Tsk_Perf_Team	5.00	1.21	5.87	.94	-3.47	74	<.001*	-1.37	-.37
Tsk_Perf_Indv	5.01	1.21	5.72	.91	-2.86	74	.006*	-1.20	-.21

Note: * Significant at a 5% significant level. The dependent variables are labelled as follows for data analysis: Diff: task difficulty; HE: heightened enjoyment; CO: control. Process: process satisfaction; Effi: efficiency. Contr_level: perceived contribution level. Real Task Perf: actual group task performance. Tsk_Perf_Team: perceived team performance on the group task. Tsk_Perf_Indv: perceived individual performance on the group task.

In conclusion, the t-test results show that when comparing the average scores of participants without synchronous manipulation to those with synchronous manipulation, those in the synchronous manipulation condition tend to report significantly more positive UX, except task difficulty (non-significant) and efficiency (marginally significant), significantly higher perceived contribution level, and significant better perceived and actual group task performance. Our hypothesis H1b, H1c, H1d, H2, H3a, H3b, and H3c are supported; H1a is not supported; and H1e is marginally supported. The hypothesis support results related to our first research question are shown in **Table 9**.

Table 9 *Significance Assessment and Hypothesis Support: T-test Results*

Hypothesis	Dependent variable	p	Hypothesis Supported?
H1a	Task difficulty	.351	No
H1b	Heightened enjoyment	.010*	Yes
H1c	Control	.006*	Yes
H1d	Process satisfaction	.031*	Yes
H1e	Efficiency	.072	Marginally supported
H2	Perceived contribution level	.030*	Yes
H3a	Actual group task performance	<.001*	Yes
H3b	Perceived team performance on group task	<.001*	Yes
H3c	Perceived individual performance on group task	.006*	Yes

Note: * Significant at a 5% level.

5.3 Moderation Effects of Individual Spatial Ability

The moderation analysis results are presented in **Table 10.** Overall, the moderation effects of individual spatial ability are only significant on the relationships between manipulation synchronicity and task difficulty, manipulation synchronicity and perceived individual performance on the group task, and manipulation synchronicity and actual group task performance.

Individual spatial ability moderation effects are not significant on the remaining relationships. Each moderation hypothesis will now be explored individually.

Table 10 *Individual Spatial Ability Moderation Effects Analysis and Hypothesis Support Results*

X variable	Y Variables		Hypothesis	p	Hypothesis Supported?
Manipulation synchronicity	Task difficulty		H1a-M	.048*	Yes
	Cognitive absorption	Heightened enjoyment	H1b-M	.896	No
		Control	H1c-M	.971	No
	Process satisfaction		H1d-M	.443	No
	Efficiency		H1e-M	.281	No
	Perceived contribution level		H2-M	.258	No
	Actual group task performance		H3a-M	.041*	Yes
	Perceived team performance on group task		H3b-M	.166	No
	Perceived individual performance on group task		H3c-M	.001*	Yes

Note: * Significant at a 5% significance level. Manipulation synchronicity (0- without-synchronous manipulation; 1- with synchronous manipulation)

5.3.1 Significant Moderation Effects of Individual Spatial Ability

At a 5% significance level, a significant moderation effect is detected in the relationship between manipulation synchronicity and task difficulty ($p = 0.048 < 0.05$). The linear model of predictions of task difficulty is shown in **Table 11**.

Table 11 *Linear Model of Predictions of Task Difficulty*

	b (Effect)	SE	t	p
Constant	6.46 [4.05, 8.86]	1.21	5.36	<.001
Manipulation Synchronicity	-1.69 [-3.19, -.19]	.75	-2.24	.028
MRT Grade	-0.25 [-.49, -.012]	.12	-2.10	.040
Manipulation Synchronicity * MRT Grade	.15 [.002, .31]	.08	2.02	.048*

Note: 95%CI. R^2=.07. *Significant at 5% level.

Our Interpretations of the moderation effect of individual spatial ability on the relationship between manipulation synchronicity and task difficulty is as follows (see **Table 12, Figure 6**):

- When MRT grades are low, there is a significant negative relationship between manipulation synchronicity and task difficulty, b= -0.999, 95% CI [-1.94, -0.06], t = -2.13, p= 0.037 < 0.05.
- At the mean value of MRT grade, at a 5% significance level, manipulation synchronicity does not have a significant impact on perceived task difficulty, b= -0.33, 95% CI [-0.99, .33], t= -0.99, p= 0.328 > 0.05.
- When MRT grades are high, at a 5% significance level, manipulation synchronicity does not significantly impact perceived task difficulty, b= .35, 95% CI [-0.59, 1.28], t=.74, p= 0.465 > 0.05.

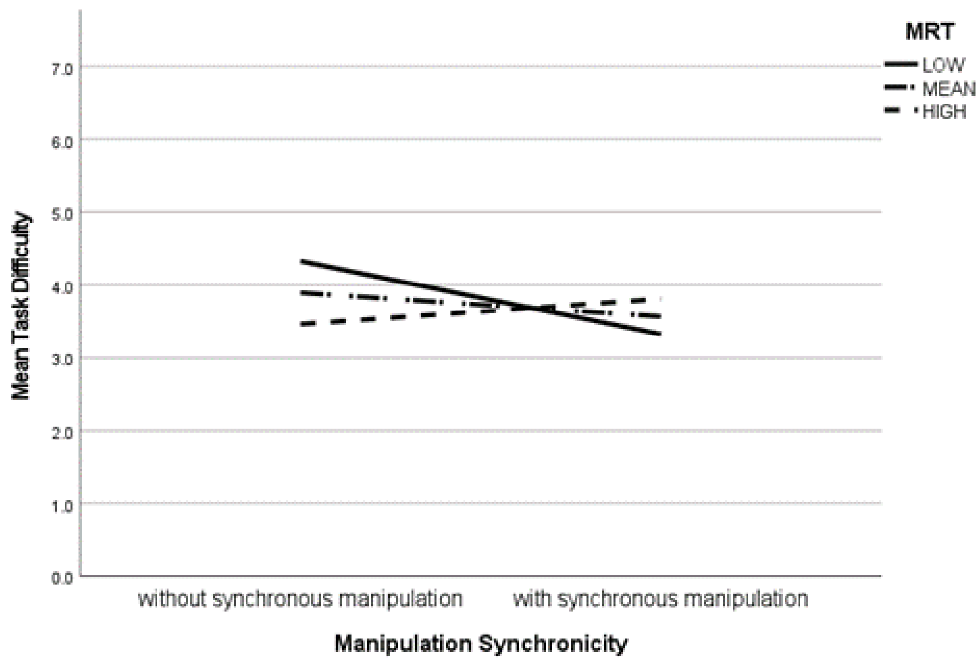
These results show that the relationship between manipulation synchronicity and task difficulty level only significantly emerges in people with low spatial ability. Additionally, **Figure 6** further reveals that for individuals with higher spatial ability, the relationship between synchronous manipulation and task difficulty tends to be weaker than for individuals with low spatial ability. **Thus H1a-M is supported.**

Table 12 *Conditional Effects of Manipulation Synchronicity on Task Difficulty at Different Values of Individual Spatial Ability*

MRT	b(Effect)	SE	t	p	LLCI	ULCI
low	-0.999	0.47	-2.13	.037*	-1.94	-0.06
mean	-0.33	.33	-0.99	.328	-0.99	.33
high	.35	.47	.74	.465	-0.59	1.28

Note: *Significant at a 5% significance level.

Figure 6 *Multiple Line Mean of Task Difficulty by MRT*



At a 5% significance level, a significant moderation effect is detected on the relationship between manipulation synchronicity and actual group task performance ($p = 0.041 < 0.05$). The linear model of predictions of actual group task performance is shown in **Table 13**.

Table 13 *Linear Model of Predictions of Actual Group Task Performance*

	b (Effect)	SE	t	p
Constant	6.97 [-3.89, 17.83]	5.45	1.28	. 205
Manipulation Synchronicity	13.16 [6.37, 19.95]	3.41	3.86	. 001
MRT Grade	1.26 [.18, 2.35]	.54	2.32	.023
Manipulation Synchronicity * MRT Grade	-.72 [-1.41, -.03]	.35	-2.08	.041*

Note: 95%CI. R^2=.26. * Significant at a 5% significance level

Our Interpretations of the moderation effect on the relationship between manipulation synchronicity and actual group task performance is as follows (see **Table 14**, **Figure 7**):

- When MRT grades are low, there is a significant positive relationship between manipulation synchronicity and actual group task performance, b= 9.92, 95% CI [5.68, 14.15], t= 4.67, p < 0.0001.
- At the mean value of MRT grade, there is a significant positive relationship between manipulation synchronicity and actual group task performance, b= 6.78, 95% CI [3.79, 9.76], t= 4.53, p < 0.0001.
- When MRT grades are high, at a 5% significance level, manipulation synchronicity does not have a significant impact on actual group task performance, b= 3.64, 95% CI [-0.60, 7.870], t= 1.710, p = .091 > 0.05.

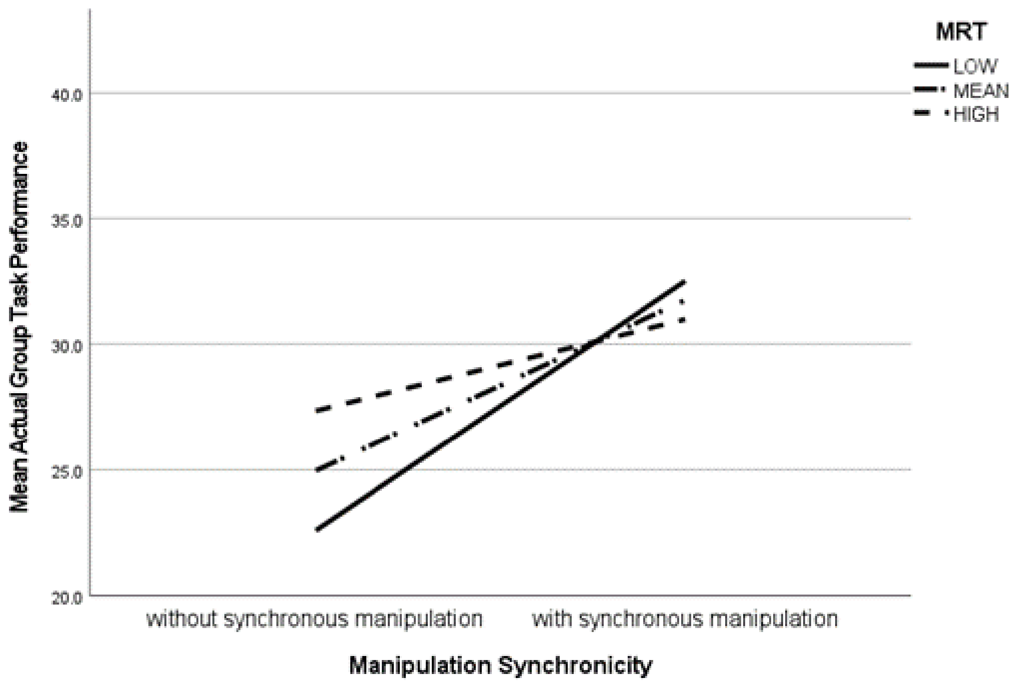
These results tell us that the relationship between manipulation synchronicity and actual group task performance on the group tasks only emerges in individuals with average and lower spatial ability. **Figure 7** further reveals that for individuals with higher spatial ability, the relationship between manipulation synchronicity and actual group task performance on the group task will be weaker than for individuals with low spatial ability. **Thus, H3a-M is supported.**

Table 14 *Conditional Effects of Manipulation Synchronicity on Actual Group Task Performance at Different Values of Individual Spatial Ability*

MRT	Effect	SE	t	p	LLCI	ULCI
low	9.92	2.12	4.67	< .0001*	5.68	14.15
mean	6.78	1.50	4.53	< .0001*	3.79	9.76
high	3.64	2.12	1.71	.091	-.60	7.87

Note: * significant at a 5% significance level.

Figure 7 *Multiple Line Mean of Actual Group Task Performance by MRT*



At a 5% significance level, there is a moderation effect on the relationship between manipulation synchronicity and perceived individual task performance on the group task ($p = 0.001 < 0.05$). The linear model of predictions of perceived individual performance on the group task is shown in **Table 15**.

Table 15 *Linear Model of Predictions of Perceived Individual Performance on the Group Task.*

	b (Effect)	SE	t	p
Constant	1.58 [-.09, 3.25]	.84	1.89	.063
Manipulation Synchronicity	2.31 [1.26, 3.35]	.52	4.40	<.001
MRT Grade	.30 [.14, .47]	.08	3.61	.001
Manipulation Synchronicity * MRT	-.18 [-.28, -.07]	.05	-3.37	.001*

Note: 95%CI. R^2=.24. * Significant at a 5% significance level

Our interpretations of the moderation effect on the relationship between manipulation synchronicity and perceived individual performance on the group task is as follows (see **Table 16**, **Figure 8):**

- When MRT grades are low, at a 5% significance level, there is a significant positive relationship between manipulation synchronicity and perceived individual performance on the group task, b= 1.50, 95% CI [0.85, 2.15], t = 4.60, p < 0.001.
- At the mean value of MRT grade, there is a significant positive relationship between manipulation synchronicity and perceived individual performance on the group task, b= .72, 95% CI [.26, 1.18], t = 3.13, p= 0.003 < 0.05.
- When MRT grades are high, at a 5% significance level, manipulation synchronicity does not have s significant impact on perceived individual performance on the group task, b= -0.06, 95% CI [-0.71, .59], t = -0.18, p = 0.857 > 0.05.

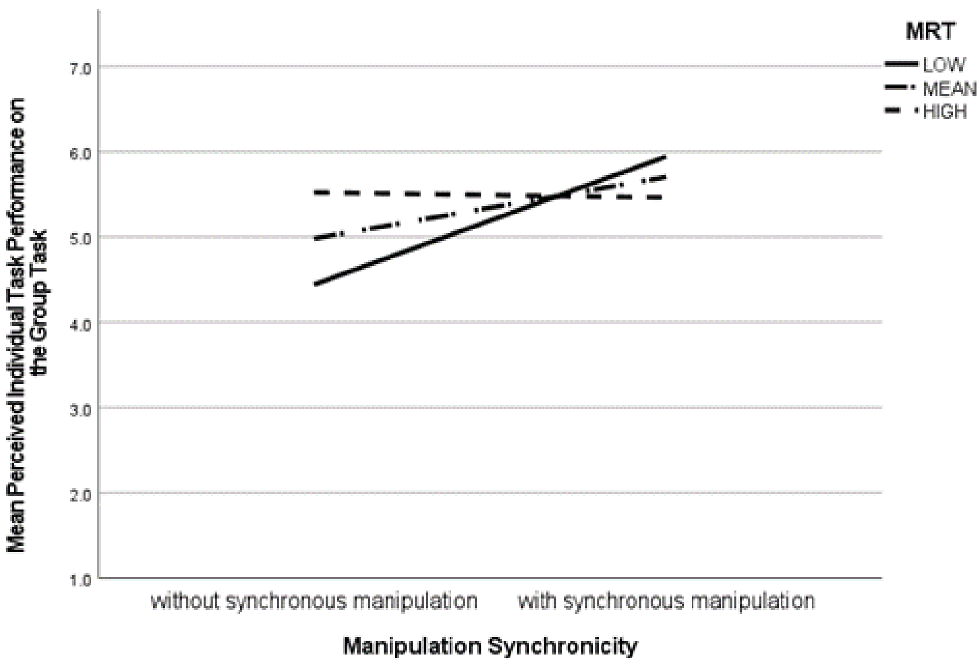
These results demonstrate that the relationship between manipulation synchronicity and perceived individual performance on the group task only emerges in people with average and lower spatial ability. Additionally, **Figure 8** further reveals that for individuals with higher spatial ability, the relationship between synchronous manipulation and perceived individual performance on the group task will be weaker than for individuals with low spatial ability. **Thus, H3c-M is supported.**

Table 16 *Conditional Effects of Manipulation Synchronicity on Perceived Individual Performance on the Group Task at Different Values of Individual Spatial Ability*

MRT	Effect	SE	t	p	LLCI	ULCI
low	1.50	.33	4.60	< .001*	.85	2.15
mean	.72	.23	3.13	.003*	.26	1.18
high	-.06	.33	-.18	.857	-.71	.59

Note: * Significant at a 5% significance level

Figure 8 *Multiple Line Mean of Perceived Individual Performance on the Group Task by MRT*



A post-hoc analysis to explore how individual spatial ability moderates the relationship between role and perceived individual performance on the group task, we ran an interaction test with the role as the independent variable and individual spatial ability as a moderator. Only a significant moderation effect of individual spatial ability on the relationship between role and perceived individual performance on the group task is detected (p= 0.032 < 0.05) (see **Table 17**). No statistical impact of individual spatial ability is detected on the remaining relationships. The moderation analysis results are shown in **Table 18**.

Table 17 *Linear Model of Predictions of Perceived Individual Performance on the Group Task*

	b (Effect)	SE	t	p
Constant	6.89 [5.58, 8.21]	.66	10.48	< .0001
Role	-1.08 [-1.80, -.36]	.36	-3.00	.004
MRT Grade	-.10 [-.24, .03]	.07	-1.51	.136
Role * MRT Grade	.08 [.01, .16]	.04	2.19	.032*

Note. 95% CI. R^2=.14. * Significant at a 5% significance level.

Table 18 *Moderation Effects of Individual Spatial Ability on the Relationship Between Role and Perceived Individual Performance on the Group Task*

X variable	Moderator	Y Variables		p
Role	Individual Spatial Ability	Task difficulty		.061
		Cognitive absorption	Heightened enjoyment	.524
			Control	.718
		Efficiency		.339
		Process satisfaction		.956
		Perceived contribution level		.180
		Actual group task performance		.206
		Perceived team performance on group task		.570
		Perceived individual performance on group task		.032*

Note: * Significant at a 5% significance level. Role (1-Shared Control, 2-Individual Control, 3-Guest.)

Our interpretations of the moderation effect on the relationship between role and perceived individual performance on the group task is as follows (see **Table 19**, **Figure 9**):

- When MRT grades are low, at a 5% significance level, there is a significant negative relationship between participant role and perceived individual performance on the group task, b= -0.72, 95% CI [-1.15, -0.28], t= -3.27, p= 0.002 < 0.05.
- At the mean value of MRT grade, at a 5% significance level, there is a significant negative relationship between participant role and perceived individual performance on the group task, b= -0.36, 95% CI [-0.66, -0.07], t= -2.46, p= 0.016 < 0.05.
- When MRT grades are high, at a 5% significance level, a participant's role does not have a significant impact on perceived individual performance on the group task, b= -0.01, 95% CI [-0.44, .43], t= -0.03, p= 0.972 > 0.05.

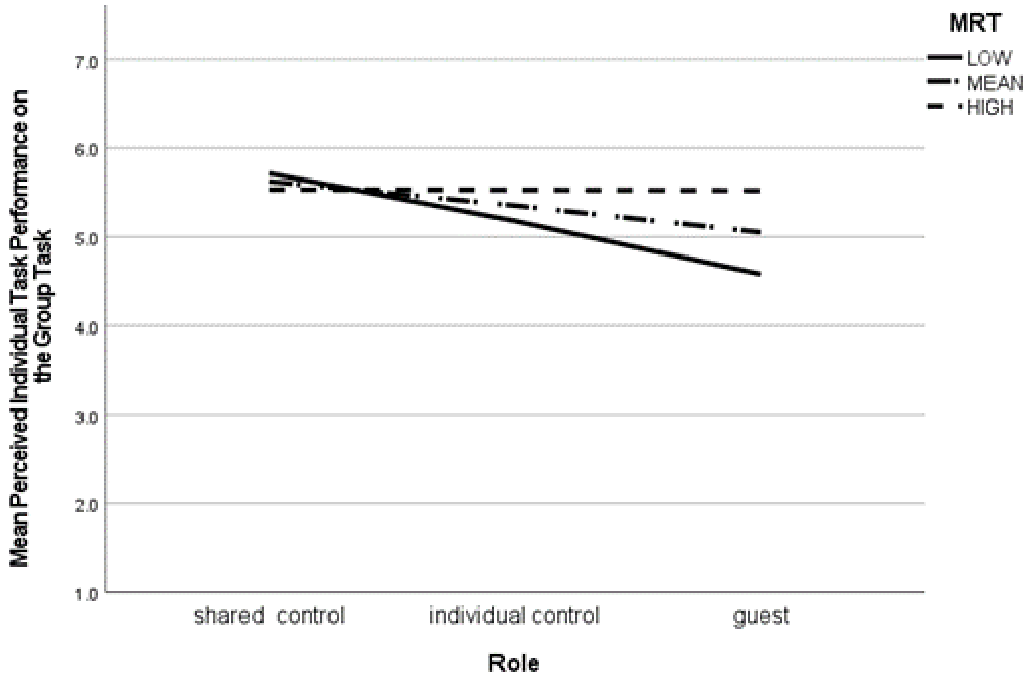
These results tell us that the relationship between participant role and perceived individual performance on the group task only emerges in users with average and lower spatial ability. Additionally, **Figure 9** demonstrates that for individuals with high spatial ability, the relationship between role and perceived individual performance on the group task will be weaker than for individuals with low spatial ability.

Table 19 *Conditional Effects of Role on Perceived Individual Performance on the Group Task at Different Values of Individual Spatial Ability*

MRT	Effect	SE	t	p	LLCI	ULCI
low	-.72	.22	-3.27	.002*	-1.15	-.28
mean	-.36	.15	-2.46	.016*	-.66	-.07
high	-.01	.22	-.03	.972	-.44	.43

Note: * Significant at a 5% significance level.

Figure 9 *Multiple Line Mean of Perceived Individual Performance on the Group Task by MRT (Post-Hoc Analysis)*



5.3.2 Non-Significant Moderation Effects of Individual Spatial Ability

The results (see **Table 10**) indicate that individual spatial ability does not have significant moderation effects on the relationships between manipulation synchronicity and the dependent variables: heightened enjoyment (p= 0.896), control (p= 0.971), and procession satisfaction (p= 0.443), efficiency (p= 0.281), perceived contribution level (p= 0.258), and perceived team performance on the group task (p= 0.166). Therefore, the hypotheses proposing that individual spatial ability moderates these relationships (H1b-M, H1c-M, H1d-M, H1e-M, H2-M, and H3b-M) are not supported.

Chapter 6: Discussion and Conclusion

In this chapter, we discuss the data analysis results in relation to the two research questions. Additionally, the limitations inherent in this study are described, and potential avenues for future research are suggested. Finally, a coherent synthesis of the entire research endeavor is provided in the form of conclusive remarks.

6.1 Discussion

6.1.1 Research Question 1

Regarding our first research question, the t-test results show that our hypotheses H1b, H1c, H1d, H2, H3a, H3b, and H3c are supported; H1a is not supported; and H1e is marginally supported (see **Table 9**). With the results, we can answer our first research question regarding how synchronous manipulation on an interactive whiteboard influences UX, contribution, and performance during virtual 3D design work. Groups in the synchronous manipulation conditions perceived significantly more positive UX, including heightened enjoyment, higher process satisfaction with the collaboration process, more control over the 3D objects and virtual scene, and marginally high perceived efficiency; however, no significant impacts were detected regarding task difficulty. Moreover, synchronous manipulation allows people to contribute as much as they want, and also increased perceived and actual group task performance.

Synchronous manipulation provides team members equal manipulation opportunities to move and edit objects in 3D design environments on IWBs. Working synchronously in those environments on IWBs is more enjoyable and engaging, and individuals are satisfied with the process. With complete and equal access to the 3D group task through 3D software/platform, individuals can participate more and therefore perceive higher technology efficiency, contribution levels, and better individual and team performance on the group task. Actual group task performance of those with synchronous manipulation is better than those without synchronous manipulation. However, synchronous manipulation did not directly influence task difficulty. This may be due to other variables influencing this relationship, as discussed in the next section.

6.1.2 Research Question 2

For research question 2 on the moderation effects of individual spatial ability, H1a-M, H3a-M, and H3c-M are supported while H1b-M, H1c-M, H1d-M, H1e-M, H2-M, and H3b-M are not supported (see **Table 10**). The significant moderation impacts of individual spatial ability are detected only in the relationships between manipulation synchronicity and task difficulty, manipulation synchronicity and actual group task, and manipulation synchronicity and perceived individual performance on the group task. No statistically significant moderation effects were detected on the relationships between manipulation synchronicity and the remaining dependent variables.

Spatial ability is a crucial factor in completing spatial design tasks and has been proven to impact task performance (Froese et al., 2013). Our moderation analysis found a significant effect of individual spatial ability on the relationship between synchronous manipulation and task difficulty, especially for users with low spatial ability. The results demonstrate that when individuals have medium or high spatial ability, it does not matter if they have synchronous manipulation. Medium and high spatial ability people can do spatial tasks well in their minds. When there is no synchronous manipulation, they can still manipulate the objects in their head and communicate the spatial information easily by using appropriate language to their partner. When individuals have low spatial ability, the synchronous manipulation access of the 3D software/platform does matter. For low spatial ability users, external 3D assistance can be beneficial. When there is synchronous manipulation, individuals with low spatial ability can use the 3D software to turn the virtual objects around because they cannot do it as well in their heads. Without synchronous manipulation, they cannot use the screen to do this and find it much more challenging to process the spatial information in their mind. Thus, the task is perceived as more difficult.

For perceived individual performance on the group task and actual group task performance, when individuals have high spatial ability, it does not matter if they have synchronous manipulation. They feel they complete the 3D design task well enough. With synchronous manipulation, they can control the virtual 3D objects themselves directly; without synchronous manipulation, they can complete the tasks in their head and communicate the spatial information smoothly with their partner, so either way, they can perform well. Conversely, synchronous manipulation is important for individuals with medium or low spatial ability. When there is synchronous manipulation, their perceived individual performance on the group task and actual group task performance is better when compared to those without synchronous manipulation.

Apart from the above significant moderation effects, individual spatial ability did not exert a statistically significant influence on the relationships between manipulation synchronicity and the remaining dependent variables. These variables encompass cognitive absorption (heightened enjoyment, control), process satisfaction, efficiency, perceived individual contribution, and perceived team performance on the group task. The impact of synchronous manipulation on those aspects was not significant for different levels of spatial ability.

6.2 Limitations

Our research has some limitations, which are also viewed as opportunities for future work. One potential limitation is our sample. The participants in our sample of 76 had similar ages and educational backgrounds (most are Master's students). Also, we only examined a two-person collaboration. Deng et al.(2022) and Stone et al. (2017) mentioned that team size could be a factor impacting 3D collaborations. Changing the team size as well as re-treating our model with a more varied sample are two directions for future research.

Data type is a second limitation. For the measures, we only collect quantitative data during and after the experiment. We did not include qualitative data via interview following the experiment. We did not code the recordings of behavioral data. Future research could triangulate our results with qualitative on actual behavioural data.

Another limitation is related to individual spatial ability. We only measured participants' mental rotation ability by MRT but did not include all subcomponents of individual spatial ability. According to spatial ability research, multiple factors have been proven to impact overall spatial ability, such as mental rotation, spatial visualization, spatial orientation, and speeded rotation (Carroll & B, 1993; Hegarty & Waller, 2005; Lohman, 1996). We measured mental rotation ability because it is the most relevant factor to the experiment task design. The group 3D design task requires lots of moving and rotation of the objects. Future research could examine the other aspects of spatial ability.

The last limitation was a technical issue. The 3D design tool, Tinkercad, is an online (web-based) 3D collaboration platform with an inherent technical issue with its real-time collaboration. Dere & Kalelioglu (2020) also mentioned this issue in their research. However, their experiment was done individually, so the issue was not very pronounced. Some groups, especially those under synchronous manipulation conditions, reported that when they edited the project simultaneously, the platform requested frequent refresh manipulations, making participants feel the technology was not very efficient. Synchronous manipulation may make the task more difficult. For those without synchronous manipulation, only one person in a group has individual control over Tinkercad; the system did not send many refresh requests to interrupt the group task. We dropped the data for several groups due to the severity. However, even with the added technical issue, we did find some significant benefit effects of synchronous manipulation. As these 3D design collaborative work environments become more reliable, future research can study even more nuanced outcomes of synchronous manipulation.

6.3 Future Work

Building upon our study's findings on the effects of synchronous manipulation in virtual 3D design work, as well as the moderating influence of individual spatial ability, there is a compelling need for further research to enhance the UX, contribution, and performance across diverse users engaged in various virtual 3D design tasks through IWBs. Our current study suggests several promising avenues for future research in this domain.

Firstly, we propose extending our research on the impact of synchronous manipulation in virtual 3D construction planning tasks completed on IWBs to include other 3D tasks, such as 3D modeling. A pertinent research question to investigate is **how synchronous manipulation affects UX, contribution, and performance in 3D modeling design tasks on IWBs**. In our study, the effects of synchronous manipulation were significant in various dimensions, including cognitive absorption, process satisfaction, efficiency, perceived contribution level, perceived individual and team performance, and actual group task performance in the context of 3D construction planning. However, Phadnis and colleagues' (2021) study on 3D modeling using 3D design software yielded different results. Their findings showed no significant difference in user satisfaction but a difference in the quality of final design work, where the group with synchronous manipulation completed tasks faster, and the group without synchronous manipulation produced higher-quality designs. Several factors, including individuals' spatial ability or their user experience during the task, such as heightened enjoyment or perceptions of task difficulty could shed light into the differing results herein. In addition, this avenue for future research could also offer valuable guidance on enhancing user experience and collaboration as well as optimizing configurations of the 3D design environments for different collaborative 3D design tasks.

Secondly, we recommend that future research should focus on examining the communication interactions among team members when employing 3D technology with different functionalities (i.e., with synchronous manipulation vs. without synchronous manipulation). The idea would be to explore **how different types of manipulation (i.e., with synchronous manipulation vs. without synchronous manipulation) influence interactions and communication patterns within a team.** This can be accomplished through the analysis and coding of video recording including user behaviors and screen activities of team members. More specifically and given that our study primarily concentrated on perceived contribution level, studying actual communication interactions among team members can complement this study's findings that show that users perceive higher levels of contribution when synchronous manipulation is employed. This would also complement current studies, like that of Phadnis et al (2021), who found that team members communicate less frequently and engage more with the 3D application in conditions with synchronous manipulation. Incorporating qualitative data in the form of video recordings that can be later analyzed and coded, can offer a more complete understanding of user behavioral differences and ultimately, performance outcomes. Additionally, given that our results, consistent with past research (e.g. Dere & Kalelioglu, 2020; Froese et al., 2013) show that manipulation of 3D design technology significantly increased perceived individual task performance for those with low spatial ability, recording and analyzing the interaction of team members among themselves as well as with technology will help in understanding the processes behind better performance perceptions.

Finally, a specific challenge of IWB lies on how to mitigate long-time manipulation fatigue. IWBs are large screens, thus participants reported that lifting their arms for 30 minutes was tiring. This discomfort introduces an element of user dissatisfaction and could potentially deter the overall usability of the technology. Additionally, some users expressed a preference for more conventional input methods, such as a mouse and keyboard, for manipulating virtual 3D objects. This preference underscores the importance of designing interfaces catering to users' comfort and ergonomic needs, thereby potentially augmenting their engagement and interaction with synchronous 3D design platforms on IWBs. Thus, future research could be conducted **to explore different input options and their influence on UX, contribution, and performance when collaborating on a 3D task.**

6.3 Conclusion

After conducting 38 rigorous controlled laboratory experimental sessions and employing statistical analysis, our research has found that synchronous manipulation yields some favorable influences on UX. This includes effects on cognitive absorption (heightened enjoyment and control), process satisfaction, and efficiency when collaborating on a 3D design task on an IWB. Furthermore, the results of our research indicate that with synchronous manipulation in a 3D environment, people feel they contribute more, individual and team task performance are perceived as higher, and they have better actual performance on the group task.

Our investigation also shows the important role that individual spatial ability has in 3D virtual collaborations on IWBs. Individuals with medium to low spatial ability appear to benefit more from the synchronous manipulation feature. By allowing them to rotate and move 3D objects, they could do the task better and communicate with their team members more easily. This enhanced interactions with the technology and partners, in turn, translating into lower perceived task difficulty and higher perceived individual task performance on the group design task. Our findings extended the findings of previous studies on individual non-collaborative design tasks (e.g., Chang, 2014; Dere & Kalelioglu, 2020), which have proved that using 3D environments such as 3D software and web-based 3D platforms is more beneficial for low spatial ability users. Differing from their experiments with individuals, we investigated a 2-person collaborative 3D design task on IWBs. Consequently, we advocate incorporating synchronous manipulation capabilities within the platform/software for virtual 3D design tasks on IWBs. This strategic enhancement can amplify such collaborations' effectiveness and user experience significantly.

This research also extends previous research (Buisine et al., 2012; Mabrito, 2006; Rahman et al., 2013a; Rogers et al., 2009; Stone, Salmon, Hepworth, Gorrell, et al., 2017a; Valérie Maquil et al., 2021; Yim et al., 2017) on synchronous manipulation benefit collaboration during general 2D tasks to 3D design tasks on IWBs, as well as 3D design tasks on computers and AR/VR environments (Eves et al., 2018; Hong et al., 2019; Phadnis et al., 2021; Schouten et al., 2016; Stone, Salmon, Eves, et al., 2017; Zhou et al., 2020) to those 3D tasks on IWBs. Our findings also enrich the research on synchronous collaborations in 3D design environments, particularly as facilitated by IWBs as we directly compared 3D virtual collaboration with and without synchronous manipulation. The specific emphasis on synchronous manipulation and the notion of shared control over the 3D objects expand the existing body of knowledge in this domain. With these outcomes in mind, we recommend that all 3D design platforms and software integrate the synchronous manipulation functionality into their products. This recommendation is substantiated by our findings that such functionality can improve collaborative task outcomes, particularly among individuals characterized by medium to low spatial ability. These individuals significantly benefit from synchronous manipulation, and this functionality can significantly improve their UX, perceived contribution level, and task performance during 3D group work.

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Appendices

Appendix A: *Literature Review _ Section 2.1 Article Summary*

Article	Affective Reaction	Effective Reaction	Contribution	Task Performance
(Gu et al., 2011)	+	+	+	
(Deng et al., 2022)				-
(Phadnis et al., 2021)	Mixed	+	+	Mixed
(Schouten et al., 2016)	+	+		+
(Hong et al., 2016)	+	+		Mixed
(Stone, Salmon, Hepworth, Red, et al., 2017)		+	+	
(Gül & Maher, 2009)	+	+	+	
(Rahman et al., 2013)	+			+
(Mabrito, 2006)	+	-	+	
(Yim et al., 2017)		+	+	+
(Stone, Salmon, Hepworth, Gorrell, et al., 2017)	+		+	
(Eves et al., 2018)		+	+	+
(Mateescu et al., 2021)				+
(Buisine et al., 2012)	+		+	+
(Chen et al., 2021)	+			+
(Valérie et al., 2021)			+	+
(Rogers et al., 2009)			+	
(Mariz et al., 2017)	-			+

Article	Affective Reaction	Effective Reaction	Contribution	Task Performance
(Kubicki et al., 2019)	+	-	+	-
(Schipper & Yocum, 2016)	+			
(Zillner et al., 2014)	+	+		+
(Siemon et al., 2017)	+	+		+

Note: + represents positive effects discussed in the study.

- represents negative effects discussed in the study.

Mixed represents both negative and positive effects discussed in the study.

Appendix B: *Instructions for Participants*

Instructions For Participants

(For Groups with Synchronous Manipulation)

1. Collaboration guideline:

You are an urban planner working on a project for a construction company, you will collaborate with another colleague remotely to develop a safe, convenient, and harmonious layout design proposal for the Joly Community based on a pre-designed map.

Tools:

- **Zoom**: You will use the Zoom Meeting to communicate with your colleague.
- **Tinkercad**: This is a real-time design collaboration platform. Both you and your partner can edit this project at the same time.

2. Task guideline:

This is a group task, both of you need to contribute, please work together.

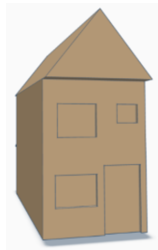
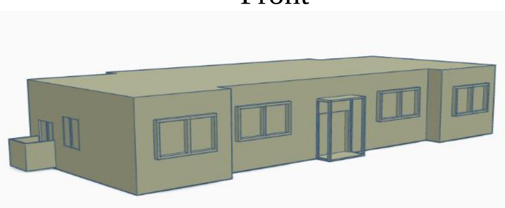
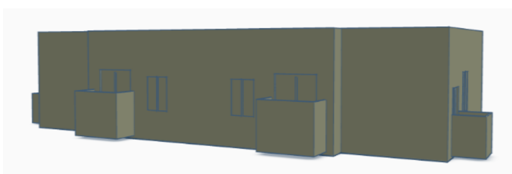
- **Time limit:** within 30 minutes.
- **You need to:**
  - Discuss and plan with your partner.
  - Following the requirements from section *3. Project Mandate* and section *4. Detailed Requirements* for each building.
  - Add buildings to the map from “Your creation” in the right panel, change building location and direction.

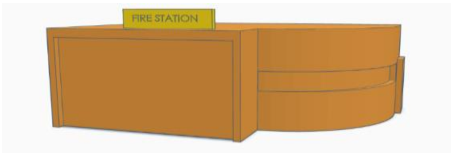
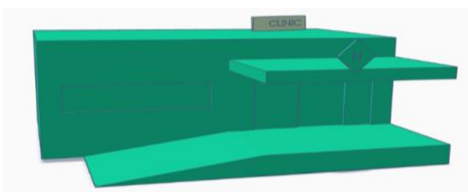
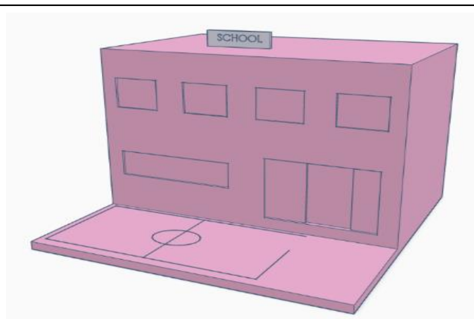
3. Project Mandate:

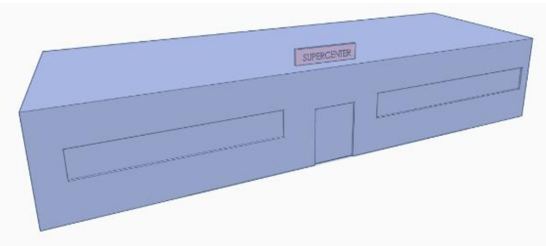
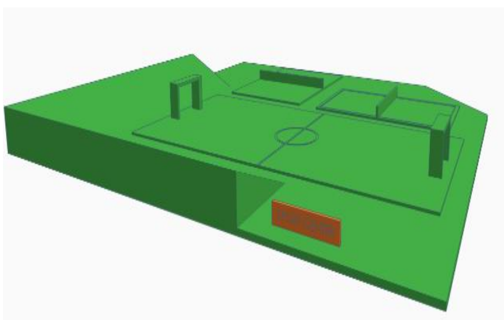
<table>
<tr><td rowspan="4">**Ensure Living Standard**</td><td colspan="2">1) Joly Community aims to fit **200 residents**, including 50 children.
2) **120** of people live in Houses. **80** of people live in Apartments.</td></tr>
<tr><td colspan="2">**ALL the following** infrastructures must be included in your final proposal:</td></tr>
<tr><td>● Have **2 types** of residential buildings: Houses and Apartments.
● A fire station
● A police station</td><td>● A medical clinic
● A school
● A shopping center
● A sports center</td></tr>
<tr><td colspan="2">Please pay attention to distinguishing the **front and back** of buildings. Check section *4. Detailed Requirements.*</td></tr>
<tr><td>**Safety& Environmental Constrains**</td><td colspan="2">1) The community's basic layout (roads, river, and plants) and all infrastructures are pre-designed and size locked. Don't change them.
2) Please **DO NOT** build any infrastructures on trees, roads, floating in the air, or out of map. (See subsequent pages section *4. Detailed Requirements*.
3) All buildings over 1 story (House, School, High Apartment,) cannot be beside the river (**should cross at least one road).** Check section *4. Detailed Requirements*.</td></tr>
</table>

4. Detailed Requirements:

For all the other infrastructures: click and add buildings from **"Your creations"** in the right panel.

Infrastructure picture	Descriptions
  Front Back	**House** 1) Each House can fit **6** residents maximum. 2) Houses in your final proposal must fit **120** of Joly community residents in total. 3) House **front door** must face one road. 4) Houses **cannot be beside the river**.
Front  Back 	**Basic Apartment** Apartment is provided with one basic 1-floor, 4-unit building model**. <u>You need to manipulate the basic building model to build higher apartment</u>**<u>(s</u>). – Each unit fits 2 residents maximum. So, **each floor fits 8 people** in total. All apartments in this community fit **80** residents in total. – **No more than 6 floors** for each final apartment. – Includes at least one apartment **over 4 floors**. – **Front door** of the apartment must face one road. – **Cannot** be beside the river if it's higher than 1 floor. – Floors should **align up and down**.

Infrastructure picture	Descriptions
 Front	**Fire Station** One fire station serves one community. It's a 1-floor building. – Must face the **main** road (the black road).
 Front	**Police Station** One police station guards one community. It's a 1-floor building. – Must face the **main** road (the black road).
 Front	**Medical Clinic** One medical clinic serves one community. It's a 1-floor building. – **Beside a road** (but do not need to face that road). It's more convenient if the building name faces one road.
 Front	**School** This school building can fit up to 100 students. – **Beside a road**. It's more convenient if the building name faces one road. – **Cannot be beside the river.**

Infrastructure picture	Descriptions
Front 	**Super center** This 1-floor super center provides types of living basics, including grocery stores, clothing stores etc. It can serve up to 250 people. – **Beside a road**. It’s more convenient if the building name faces one road.
 Front	**Sports Center** Can support 300-people events. It's a 1-floor building. – **Beside a road**. It’s more convenient if the building name faces one road.

Instructions For Participants

(For Groups without Synchronous Manipulation with Control)

1. Collaboration guideline:

You are an urban planner working on a project for a construction company, you will collaborate with another colleague remotely to develop a safe, convenient, and harmonious layout design proposal for the Joly Community based on a pre-designed map.

Tools:

- **Zoom**: You will use Zoom Meeting to communicate and collaborate with your colleague.
- **Tinkercad**: Only you can edit this project. Your colleague can join the progress in real-time using the Zoom screen share functionality but cannot edit it.

2. Task guideline:

This is a group task, both of you need to contribute, please work together.

- **Time limit:** within 30 minutes.
- **You need to:**
  - Discuss and plan with your partner.
  - Following the requirements from section *3. Project Mandate* and section *4. Detailed Requirements* for each building.
  - Add buildings to the map from "Your creation" in the right panel, change building location and direction.

3. Project Mandate:

Note: this section is the same as Instructions for Participants (For Groups with Synchronous Manipulation).

4. Detailed Requirements:

Note: this section is the same as Instructions for Participants (For Groups with Synchronous Manipulation).

Instructions For Participants

(For Groups without Synchronous Manipulation without Control)

1. Collaboration guideline:

You are an urban planner working on a project for a construction company, you will collaborate with another colleague remotely to develop a safe, convenient, and harmonious layout design proposal for the Joly Community based on a pre-designed map.

Tools:

- **Zoom**: You will use Zoom Meeting to communicate and collaborate with your colleague.
- **Tinkercad**: Only your colleague can edit this project. You can join the progress in real-time using the Zoom screen share functionality, but you cannot edit it.

2. Task guideline:

This is a group task, both of you need to contribute, please work together.

- **Time limit:** within 30 minutes.
- **You need to:**
  - Discuss and plan with your partner.
  - Following the requirements from section *3. Project Mandate* and section *4. Detailed Requirements* for each building.

3. Project Mandate:

Note: this section is the same as Instructions for Participants (For Groups with Synchronous Manipulation).

4. Detailed Requirements:

Note: this section is the same as Instructions for Participants (For Groups with Synchronous Manipulation)

Appendix C: *Measures*

Variable & Reference	Item
Task difficulty (Fisher & Noble, 2004)	*Diff1: very simple/ very complex *Diff2: very easy/ very difficult Diff3: routine/ novel
Cognitive absorption (Agarwal & Karahanna, 2000)	Temporal Dissociation: TD1: Time appeared to go by very quickly. TD2: Sometimes I lost track of time. TD3: Time flew. TD4: I spent more time than I had planned. TD5: I spent more time than I had intended. Focused Immersion: FI1: I was able to block out most other distractions. FI2: I was absorbed in what I was doing. FI3: I was immersed in the task I was performing. FI4_r: I got distracted by other things very easily. FI5: My attention did not get diverted very easily. Heightened enjoyment: *HE1: I had fun. *HE2: This task provided me with a lot of enjoyment. *HE3: I enjoyed this activity. *HE4_r: This task bored me. Control: *CO1: I felt in control. *CO2_r: I felt that I had no control over my interactions. CO3: During the task, I could control my interactions. Curiosity: CU1: This task excited my curiosity. CU2: Interacting during the task made me curious. CU3: This task aroused my imagination.

Variable & Reference	Item
Process satisfaction (Lowry et al., 2009)	*Process1: Our process for collaborating as a group was efficient. *Process2_r: Our process for collaborating as a group was uncoordinated. *Process3_r: Our process for collaborating as a group was unfair. *Process4: Our process for collaborating as a group was understandable. *Process5: Our process for collaborating as a group was satisfying.
Team Decision Making Constructive controversy (O'Neill et al., 2016)	Controv1: My partner and I expressed our own views directly to each other. Controv2: We listened carefully to each other's opinions. Controv3: My partner and I tried to understand each other's concerns. Controv4: We tried to use each other's ideas. Controv5: Even when we disagreed, we communicated respectfully with each other. Controv6: We used our opposing views to understand the problem.
Relationship conflict (O'Neill et al., 2016)	Confl1: There was emotional conflict. Confl2: There was anger. Confl3: There was personal friction. Confl4: There were personality clashes. Confl5: There was tension.
Team potency (O'Neill et al., 2016)	Pot1: My partner and I could get a lot done. Pot2: My partner and I believe we would be very productive. Pot3: My partner and I feel that we could solve any problem we encounter.

Variable & Reference	Item
	Pot4: My partner and I believe we would produce high-quality work.
Ownership:	Own1: I feel like the solution we provided represents my work. Own2: I feel like the solution we provided represents my ideas. Own3: I feel like my ideas had an influence on the solution we provided. Own4: I feel like the ideas I provided were reflected in what we produced.
Contr_level:	*Contr_level1: I contributed during the group task.
Contr_equal:	*Contr_level2: I contributed to the group's work. Contr_level3_r: I could not contribute as much as I wanted to the group's work. Partner_contr1: I feel my partner contributed more than I did to our group's work. Partner_contr2_r: I feel I contributed more than my partner to our group's work. Partner_contr3: I feel I contributed less than my partner to our group's work.
Team Task performance (Fisher & Noble, 2004)	*Perf1: Ineffective/ Effective *Perf2: Poor performance/ Excellent performance *Perf3: No progress at all/ Made rapid progress *PerfX: Not successful/successful
Individual Task performance (Fisher & Noble, 2004)	*Perf1: Ineffective/ Effective *Perf2: Poor performance/ Excellent performance *Perf3: No progress at all/ Made rapid progress *PerfX: Not successful/successful

Variable & Reference	Item
UEQ (Schrepp et al., 2017)	Attractiveness: Overall impression of the product. Do users like or dislike it? Is it attractive, enjoyable or pleasing? 6 items: annoying / enjoyable, good / bad, unlikable / pleasing, unpleasant / pleasant, attractive / unattractive, friendly / unfriendly. Perspicuity: Is it easy to get familiar with the product? Is it easy to learn? Is the product easy to understand and clear? 4 items: not understandable / understandable, easy to learn / difficult to learn, complicated / easy, clear / confusing. * Efficiency: Can users solve their tasks without unnecessary effort? Is the interaction efficient and fast? Does the product react fast to user input? 4 items: fast/slow, inefficient/efficient, impractical/ practical, organized/cluttered. Dependability: Does the user feel in control of the interaction? Can he or she predict the system behavior? Does the user feel safe when working with the product? 4 items: unpredictable/predictable, obstructive/supportive, secure/not secure, meets expectations/ does not meet expectations. Stimulation: Is it exciting and motivating to use the product? Is it fun to use? 4 items: valuable/inferior, boring/exciting, not interesting/interesting, motivating/demotivating. Novelty: Is the product innovative and creative? Does it capture users' attention? 4 items: creative/dull, inventive/conventional, usual/leading edge, conservative/innovative.
Learning emotion (Robin H. Kay & Sharon Loverock, 2000)	Emo1: Not at all satisfied/Very satisfied Emo2: Not at all curious/Very curious Emo3: Not at all excited/Very excited Emo4_r: Not at all disheartened/Very disheartened Emo5_r: Not at all dispirited/Very dispirited

Variable & Reference	Item
	Emo6_r: Not at all anxious/Very anxious
	Emo7_r: Not at all insecure/Very insecure
	Emo8_r: Not at all helpless/Very helpless
	Emo9_r: Not at all nervous/Very nervous
	Emo10_r: Not at all irritable/Very irritable
	Emo11_r: Not at all frustrated/Very frustrated
	Emo12_r: Not at all angry/Very angry
Actual Task Performance	* Actual group task performance (Appendix E: Gading Criteria of The Joly Community Layout Proposal)

Note: items without * were dropped when conducting data analysis

Appendix D: *SPSS Exploratory Factor Analysis (EFA) Results of Each Variable*

For task difficulty, we asked, “How would you describe the task your team just completed?” The three items are Diff1: very simple/very complex, Diff2: very easy/very difficult, and Diff3: routine/novel. We dropped Diff3 for reliability reasons. The correlation matrix and component matrix SPSS test results are shown in **Table 20** and **Table 21** in Appendix D. In terms of cognitive absorption (Agarwal & Karahanna, 2000), only the heightened enjoyment and control, such constructs were used for data analysis. We asked, “During the group task you just completed, to what extent do you agree with the following statements. The correlation matrix and component matrix SPSS test results are shown in **Table 22** and **Table 23** in Appendix D. We used the five items from Lowry et al. (2009) to measure process satisfaction. The questions begin with “Our process for collaborating as a group was”, followed by efficient/ uncoordinated/ unfair/ understandable/ satisfying for each of the five items. The correlation matrix and component matrix SPSS test results are shown in **Table 24** and **Table 25** in Appendix D. For efficiency**,** items are from UEQ (Schrepp et al., 2017), and for the sake of reliability and interest, we kept the dimension and asked, “How would you rate your experience with the technology used in the task you just completed?” We included four items: fast/slow, inefficient/efficient, impractical/practical, organized/cluttered. The Correlation Matrix and Component Matrix SPSS test results are shown in **Table 26** and **Table 27** in Appendix D.

For perceived individual contribution, we created three items and dropped Contr_level3_r to ensure reliability. The correlation matrix and component matrix SPSS test results are shown in **Table 28** and **Table 29** in Appendix D. For perceived individual and team performance on the group task, the items are from Fisher & Noble (2004), and we measured them on both individual and team levels. The items are the same, but we asked two questions. For team task performance, we asked, “How would you rate your group’s performance on the task you just completed? How did your group perform?” Then we asked on an individual level: “How would you rate your own performance on the group task your team just completed? How did you individually perform?” The Correlation Matrix and Component Matrix SPSS test results are shown in **Table 30** and **Table 31** in Appendix D.

Table 20 *Correlation Matrix of Task Difficulty*

	Diff1	Diff2
Diff1	1.000	.577
Diff2	.577	1.000

Table 21 *Component Matrix[a] of Task Difficulty*

	Component
	1
Diff2	.888
Diff1	.888

Note: a. 1 component extracted.

Table 22 *Correlation Matrix of Heightened Enjoyment and Control*

	HE1	HE2	HE3	HE4_r	CO1	CO2_r
HE1	1.000	.867	.784	-.602	.321	-.455
HE2	.867	1.000	.763	-.524	.362	-.395
HE3	.784	.763	1.000	-.511	.322	-.464
HE4_r	-.602	-.524	-.511	1.000	-.069	.351
CO1	.321	.362	.322	-.069	1.000	-.465
CO2_r	-.455	-.395	-.464	.351	-.465	1.000

Table 23 *Rotated Component Matrix[a] of Heightened Enjoyment and Control*

	Component	
	1	2
HE1	.888	
HE2	.843	
HE3	.815	
HE4_r	-.807	
CO1		.915
CO2_r		-.711

Note: a. Rotation converged in 3 iterations.

Table 24 *Correlation Matrix of Process Satisfaction*

	Process1	Process2_r	Process3_r	Process4	Process5
Process1	1.000	-.358	-.569	.725	.788
Process2_r	-.358	1.000	.271	-.392	-.372
Process3_r	-.569	.271	1.000	-.413	-.551
Process4	.725	-.392	-.413	1.000	.568
Process5	.788	-.372	-.551	.568	1.000

Table 25 *Component Matrix[a] of Process Satisfaction*

	Component
	1
Process1	.910
Process5	.864
Process4	.809
Process3_r	-.718
Process2_r	-.562

Note: a. 1 component extracted.

Table 26 *Correlation Matrix of Efficiency*

	Effi1	Effi2	Effi3	Effi4
Effi1	1.000	.637	.460	.431
Effi2	.637	1.000	.627	.546
Effi3	.460	.627	1.000	.640
Effi4	.431	.546	.640	1.000

Table 27 *Component Matrix[a] of Efficiency*

	Component
	1
Effi2	.865
Effi3	.839
Effi4	.799
Effi1	.765

Note: a. 1 component extracted.

Table 28 *Correlation Matrix of Perceived Individual Contribution*

	Contr_level1	Contr_level2
Contr_level1	1.000	.793
Contr_level2	.793	1.000

Table 29 *Component Matrix[a] of Perceived Individual Contribution*

	Component
	1
Contr_level2	.947
Contr_level1	.947

Note: a. 1 component extracted

Table 30 *Correlation Matrix of Perceived Task Performance*

	1	2	3	4	5	6	7	8
1. Tsk_Perfm_Team1	1.000	.730	.758	.787	.636	.460	.525	.548
2. Tsk_Perfm_Team2	.730	1.000	.636	.717	.586	.594	.425	.580
3. Tsk_Perfm_Team3	.758	.636	1.000	.850	.526	.364	.652	.626
4. Tsk_Perfm_TeamX	.787	.717	.850	1.000	.639	.476	.580	.733
5. Tsk_Perfm_Indv1	.636	.586	.526	.639	1.000	.777	.666	.747
6. Tsk_Perfm_Indv2	.460	.594	.364	.476	.777	1.000	.588	.639
7. Tsk_Perfm_Indv3	.525	.425	.652	.580	.666	.588	1.000	.741
8. Tsk_Perfm_IndvX	.548	.580	.626	.733	.747	.639	.741	1.000

Table 31 *Component Matrix*[a] *of Perceived Task Performance*

	Component
	1
Tsk_Perfm_TeamX	.886
Tsk_Perfm_IndvX	.855
Tsk_Perfm_Indv1	.847
Tsk_Perfm_Team1	.832
Tsk_Perfm_Team3	.828
Tsk_Perfm_Team2	.801
Tsk_Perfm_Indv3	.785
Tsk_Perfm_Indv2	.736

Note: a. 1 component extracted.

Appendix E: *Gading Criteria of The Joly Community Layout Proposal.*

	Rule Details	Points
1	Fit 200 residents	3
2	Buildings are not floating	4
3	Buildings cannot be built on the road	1
4	Buildings cannot be built on the trees	1
5	Buildings cannot be built out of map	3
6	No houses, multi-story apartments and school buildings beside the river.	3
7	Proper house number	1
8	All houses (front door) must face at least one road	2
9	Proper multi-story apartment number	3
10	Front door of apartment buildings must face one road	1
11	Apartment floors align up and down	5
12	Have one fire station	1
13	Fire station must face the main road	2
14	Have one police station	1
15	Police station must face the main road	2
16	Have one medical clinic	1
17	Medical clinic needs to be beside a road.	1
18	Have one school	1
19	School needs to be beside a road	1
20	Have one super center	1
21	Super center needs to be beside a road.	1
22	Have one sports center	1
23	Sports center needs to be beside a road	1
	Total Grade	41

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