Master's Thesis Academic Year 2025

# Development and Evaluation of Supernumerary Robotic Limb Control Strategies and Sense of Embodiment in a Virtual Reality Environment

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July 2025

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# Thesis Abstract

This work presents the development of a modular Virtual Reality (VR) environment in Unreal Engine 5, created to address the need for a standardized and accessible testing environment in the field of Supernumerary Robotic Limbs (SRL). The platform's main design principle is modularity, which allows researchers to easily integrate and evaluate diverse control paradigms. To illustrate this capability, a number of basic control strategy options were implemented, ranging from direct manual modes (polar coordinates, retargeting, mirroring) to a task-aware autonomous system driven by a Finite State Machine (FSM).

The platform was subsequently used in an initial user study comparing performance on a fairly complex assembly task across 3 distinct conditions: unassisted work, collaboration with the autonomous SRL and teaming up with a traditional external cobot. A rich set of measurements was collected, including objective performance, subjective workload, user experience and user embodiment. The work details the technical implementation of key features such as physics-based object manipulation, tool usage, and autonomous agent behavior.

Although a detailed comparative analysis of every implemented control scheme was beyond the scope of this thesis, the modular approach and initial investigation provide a robust testbed and path towards future explorations into intuitive control, user embodiment and the next generation of human augmentation technologies.

# Acknowledgment

Completing this thesis has been a profound journey of academic and personal growth, an international experience made possible only through the collective guidance and support of many individuals.

I am incredibly grateful to my supervisors, Professor Maki Sugimoto, Professor Jean-Marie Normand and Associate Professor Rebecca Fribourg. Your insightful feedback sharpened my analytical skills and your constant encouragement gave me the confidence to navigate the complexities of this research. Thank you for investing so much of your time and knowledge in my growth.

My sincere gratitude extends to the JEMARO program. This international master's degree was a truly transformative opportunity, both academically and personally.

To my friends and colleagues in the JEMARO group: thank you for being the ideal companions for this adventure in Japan. Our late-night discussions, shared struggles, and friendly and effortless bond forged a community that was both intellectually stimulating and deeply supportive; it was crucial to this journey.

I am also deeply thankful for my family. To my parents and my brother, your unwavering belief in my pursuits, even across thousands of miles, has been a constant source of strength and instrumental to my success.

Ultimately, this thesis reflects not just my own work, but the collective support of everyone who has shaped my academic and personal life. This journey has taught me invaluable lessons that extend far beyond academia, highlighting the value of critical questioning and the importance of diverse perspectives in solving both engineering and life's challenges. It has sparked a lasting passion for contributing to the dynamic field of human-robot interaction. Above all, it has been a transformative chapter of personal growth, for which I am deeply and forever grateful.

# Contents

# Chapter 1

# Introduction

## 1.1 Background

### 1.1.1 Supernumerary Robotic Limbs: Concept and Potential

Supernumerary Robotic Limbs (SRLs) are a novel category of wearable robots built to enhance human capabilities by adding extra limbs, such as additional arms or legs. These robotic extensions are combined with the human body, working in teams with both the user's natural limbs and potentially other mechanical systems to offer an enhanced level of support and assistance [13,21]. The motivation of SRLs is to go beyond the limitations of the human body by providing additional degrees of freedom, allowing humans to perform tasks that would otherwise be impossible, unsafe, or require the cooperation of multiple people [1].

SRLs have the potential to make a positive impact across various fields. They may improve mobility, coordination, and the ability to multitask effectively [1, 13, 14]. For example, in manufacturing, SRLs can support workers with complex assembly tasks and heavy lifting, making the work process smoother and safer by decreasing injury risks [21]. The same is true in agriculture, where these systems can be a big help for tasks that require reaching up high or managing more than one tool at once. There could also be benefits for the healthcare industry, for example in surgery, patient care or enabling people with disabilities to do more by themselves.

By boosting our natural abilities, SRLs allow us to tackle more complex problems and push beyond the physical limitations we currently face in different activities. However, it's important to design and develop such systems carefully, so that the user has a sense of control over the device and it becomes an extension of their own bodies [1, 9].

### 1.1.2 Challenges in SRLs: Control and Embodiment

Despite the great potential, the development and actual use of SRLs face significant challenges, especially in regards of control strategies and user embodiment. These two aspects are closely related and are essential for the seamless integration of SRLs with human users [1].

The first key challenge is developing effective control strategies, which define how an SRL reacts to user inputs and interacts with the environment. Designing these strategies is necessary to ensure that SRLs are not only responsive and precise, but also safe, minimizing the cognitive load on the user and preventing unintentional actions [1, 28]. The main objective is to achieve intuitive control, similar to the way one manipulates their natural limbs. This includes examining various input methods, from manual mapping to more advanced autonomous or collaborative control systems.

The second major challenge is achieving a strong sense of embodiment; this refers to the user's perception of the SRL not simply as a tool, but as an actual part of their own body [9, 25]. It is important to maximize embodiment to achieve intuitive and effective SRLs so that users can manipulate the surrounding environment naturally and effectively [5]. If users do not feel a sense of ownership over the supernumerary limbs, the cognitive effort needed to control them can increase, potentially deleting all the benefits of the augmentation.

Successfully addressing these challenges in control and embodiment is essential for realizing the full potential of SRLs and ensuring they become practical and beneficial extensions of human capability.

### 1.1.3 Virtual Reality as a Testing Environment for SRLs

Addressing the complex challenges of SRL development requires robust and flexible research methodologies. Virtual Reality (VR) has emerged as an exceptionally valuable tool in this regard, offering a powerful testing environmet for the simulation, iterative design and evaluation of SRL systems [1, 4, 9].

The use of VR environments offers multiple important benefits for SRL research. First of all, it offers a safe setting where different SRL designs and new control algorithms may be tested with less risk with respect to physical hardware (especially in the early stages of development or when trying unconventional interaction paradigms [28]). Secondly, VR is cost-effective and efficient, significantly reducing the need for expensive and time-consuming physical prototyping for each design iteration. This allows for rapid exploration and refinement of concepts. VR environments are highly customizable and controllable, allowing the creation of experimental tasks and scenarios designed to evaluate specific aspects of SRL performance, user experience or embodiment under controlled conditions. The modularity of well-designed VR simulations also makes easy the straightforward integration and comparative evaluation of different control interfaces or SRL configurations. Finally, modern VR technology can deliver high-fidelity, immersive experiences, which are crucial for studying phenomena like embodiment, as they help to increase the sense of presence and interaction realism of the user [30, 32].

By taking advantage of this, VR spaces are an excellent medium for systematically exploring how various factors affect a user's understanding and operation of SRLs, thus accelerating the development of more effective and intuitive assistive robotic systems.

### 1.1.4 Unreal Engine 5 for Advanced SRL Simulation

While VR provides a powerful general methodology for SRL research, the choice of development platform is critical for creating complex and effective simulations. Unreal Engine 5 (UE5) was chosen for this study for its rich set of advanced features and capabilities that provide compatibility and an immersive and interactive

VR environment for the SRL system complexity coverage.

The state-of-the-art physics engine in UE5, powerful and realistic, will provide benefits, given that it enables the faithful simulation of object interactions, collisions and the dynamic behavior of both the virtual environment and the SRLs. This function is essential where manipulation and assembly are involved, activities central to this research, as it provides a more natural experience for the user. Also, UE5's rendering capabilities support high-fidelity graphics, increasing the sense of presence and immersion, which is significantly important when studying user embodiment.

The engine natively supports OpenXR, making it compatible with a wide range of VR hardware and following the industry standards for XR development, to accommodate the current and future experimental setups. Another significant benefit is UE5's visual scripting system, Blueprints, which facilitates rapid prototyping and accelerates the development cycle. This was used to iteratively develop and deploy different control strategies and manipulation mechanics for the SRLs. Due to its flexibility, the engine is able to handle complex scenarios and to include different elements, including, but not limited to, different SRL control modes (manual and autonomous), tool interactions, and data logging functionalities.

In combination, these features make UE5 a robust and fitting platform to create the complex and realistic simulations needed to rigorously evaluate SRL control strategies and their impact on user performance and embodiment.

## 1.2 Problem Statement

Although SRLs attract attention as a promising concept of human augmentation, their practical implementation and widespread use are challenged by various R&D issues. The design of intuitive control schemes that allow users to manage these additional limbs effectively without unnecessary cognitive demand remains a primary obstacle [1]. At the same time, creating a strong sense of embodiment (in which the user identifies the SRLs as natural extensions of their body) is important for seamless interaction and ideal task performance, yet this remains a complex phenomenon to consistently achieve and measure [9, 25].

A significant factor slowing progress in these areas is the lack of standardized, readily adaptable, and cost-effective platforms for systematic experimentation [21]. Current research typically relies on customized physical prototypes or simulation environments, which makes it difficult to compare results across studies and to iterate new designs and control interfaces quickly. This underscores the need for a modular VR environment to act as a common testing environment, which allows researchers to readily develop, evaluate, and validate different SRL models, concrete control schemes, and interaction setups. Without such a platform, the systematic investigation into how different control paradigms affect task performance, user workload, and the development of embodiment is substantially restricted.

In addition, comparisons are lacking to benchmark more traditional robotic assistance (e.g., external cobots) worn SRLs in shared operational settings in a manner that is well-grounded in user experience and task effectiveness. Understanding the relative advantages and disadvantages of these different approaches to human-robot collaboration, particularly concerning aspects like embodiment and perceived intuitiveness, is important for guiding future development in assistive robotics. The lack of flexible and user-friendly simulation tools makes such comparative studies hard to conduct in an efficient and controlled way. This research aims to address these weaknesses by developing and validating such a modular VR environment.

## 1.3 Objectives

The main goal of this thesis is to create and evaluate a modular VR simulation environment with high visual quality based on UE5 to serve as a testbed for SRL research. The following specific objectives complement this particular goal:

- To develop an adaptable VR framework that can simulate complicated assembly tasks and offer different SRL arrangements and interaction modes.

- To implement a variety of distinctive SRL control strategies into the environment; manual (polar coordinate, retargeting, mirroring) and fundamental autonomous modes (FSM-driven, gaze-assisted) to exhibit the platform's potential for later in-depth comparative studies.
- To develop protocols in terms of experimental situations to be able to measure and compare user performance and experience in SRL-assisted conditions of various task applications to an unassisted baseline condition and to the same collaboration with a simulated external cobot.
- To include a set of objective and subjective metrics for evaluating task performance (completion time, errors), efficiency (movement smoothness, idle time), user's perceived workload (NASA-TLX), user experience, perceived collaboration and the sense of embodiment.
- To validate the developed VR environment and experimental methodology through initial user studies, providing a robust platform that simplifies the testing and evaluation of current and future SRL control interfaces and embodiment theories.

## 1.4 Research Questions

The primary questions guiding this study are:

**RQ1**: How does the utilization of an autonomous SRL for an assembly task compare to performing the same task using only natural limbs, in terms of task performance, user experience and workload?

- **Independent Variable:** Method of task execution (Condition 1: Natural limbs only vs. Condition 2: Autonomous SRL assistance).
- **Dependent Variables:** Task completion time, number of errors (dropped objects), user's perceived workload and experience (questionnaires).

**RQ2**: What are the differences in user experience and workload when collaborating on an assembly task with an autonomous wearable SRL versus an autonomous external cobot?

- **Independent Variable:** Type of autonomous robotic collaborator (Condition 1: Autonomous wearable SRL vs. Condition 2: Autonomous external cobot).
- **Dependent Variables:** User's perceived workload, Collaborative Task Experience, user experience.

**RQ3**: To what extent can users experience a sense of embodiment over a pair of supernumerary robotic arms when the limbs are operating autonomously as a collaborative partner, rather than under direct manual control?

- **Independent Variable:** This research question is descriptive and focuses on a single experimental condition. Therefore, it does not involve the manipulation of an independent variable in the same comparative manner as RQ1 and RQ2. The context under which the measurement is taken is the Autonomous SRL Collaboration condition.
- **Dependent Variables:** User's sense of embodiment.

### 1.4.1 Hypotheses

Based on the existing literature and the anticipated benefits of SRL technology, the following hypotheses are proposed:

- H1 (Related to RQ1): Participants utilizing an autonomous SRL will exhibit improved task performance (reduced task completion time, less usage of their natural limbs) for the assembly task compared to participants using only their natural limbs.

- H2 (Related to RQ2): Collaboration with an autonomous wearable SRL will result in a similarly low perceived workload (NASA-TLX) and a close perceived collaboration quality.

- H3 (Related to RQ3): Despite the lack of direct manual control, users are expected to report a significant sense of embodiment over the autonomous SRL during the collaborative assembly task. It is hypothesized that this will be particularly evident in the VEQ sub-scale of Ownership and Change in Body Schema, suggesting that factors such as visual congruency, task utility and the perceived responsiveness of the robotic partner can contribute to embodiment even when the sense of direct motor agency is low.

## 1.5 Significance of this Thesis

This thesis makes a significant contribution to the growing field of SRL research by addressing essential needs in testing methodologies and foundational understanding. The focus of the work is mainly on the creation and initial validation of an all-new, modular and high-fidelity VR Simulation platform based on UE5. This platform provides a much-needed accessible and adaptable tool for the research community, enabling the systematic, cost-effective, and safe exploration of diverse SRL control interfaces and their impact on user embodiment and task performance. By providing a structured framework for simulating complex assembly tasks while integrating different SRL operational modes, this work provides a practical solution to the current limitations associated with dependence on physical prototypes or disparate, non-standardized simulation setups.

Methodologically, this research offers a standardized approach for conducting comparative studies on SRLs. The established experimental protocols for evaluating SRL-assisted performance against unassisted human capabilities and against traditional external cobots offer a clear path for future benchmarking and technology assessment. Although a complete comparison of various different control strategies was not within the scope of this particular thesis, the development of a range of key control methods serves as proof-of-concept for the platform's potential and lays the way for such in-depth future studies.

Moreover, the preliminary results from the comparative experiments conducted in this environment (autonomous SRL vs. natural limbs, autonomous SRL vs. external cobot) are useful in the initial investigation of human-SRL interaction. These findings can help toward an understanding of task efficiency, user workload and the factors influencing the subjective sense of embodiment when using wearable robotic augmentation.

In the end, the importance of this thesis extends beyond these immediate technical developments. An embodied interactive SRL curriculum and the learned insights will inform the design of the next generation of more intuitive and effective SRL systems, advance our understanding of human-robot collaboration paradigms and potentially translate beyond to inform training protocols for users of advanced robotic augmentation technologies. This constitutes a solid base for future studies on the complex relationship of SRL control and bodily awareness.

# Chapter 2

# Literature Review

## 2.1 Introduction

This chapter provides a comprehensive review of the existing literature relevant to the development and evaluation of SRLs within VR environments. In order to systematically evaluate and organize the current state of research, a systematic process of literature review and selection was employed. This approach was guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement and standard techniques used for systematic reviews. [27]. This process was driven by specific research questions, a defined search strategy, and a multi-stage screening and quality assessment procedure.

The primary research questions (RQs) formulated to direct this review were:

- **RQ1:** What control strategies and human-machine interface (HMI) paradigms are currently being investigated for operating Supernumerary Robotic Limbs, and how do these strategies address challenges like managing additional degrees of freedom and minimizing cognitive load?

- **RQ2:** Which methods are used to evaluate user embodiment and overall user experience (UX) with Supernumerary Robotic Limbs in virtual and physical environments, and what factors are identified as significantly influencing these subjective outcomes?

The search was conducted on the Scopus database using the following query string:

```
( ( "supernumerary limb*" OR "supernumerary arm*" OR "supernumerary
robotic arm*" OR "supernumerary virtual arm" OR "supernumerary
robotic limb*" OR "supernumerary virtual limb*" ) AND ( "vr" OR "mr"
OR "virtual reality" OR "mixed reality" ) )
```

This query produced an initial set of 370 articles. The following screening process involved several stages: articles were first filtered by language (English only) and publication year (to focus on recent advancements), reducing the count to 270 papers. A title and abstract screening of relevance to the research questions reduced this to 36 articles. These 36 articles then underwent a full article screening, resulting in 23 potentially relevant to the review. Finally, the quality of these 23 papers was assessed for their relevance and applicability to the research questions. This evaluation was guided by a set of quality assessment (QA) questions:

- **QA1:** Does the research provide a sufficiently detailed description of the SRL system's design (e.g., degrees of freedom, attachment, morphology), the control interface, and the experimental task to allow for a conceptual understanding and potential replication of the setup?
- **QA2:** Does the study clearly define its outcome measures for SRL performance, UX, and/or embodiment, and does it employ appropriate methodologies (e.g., validated questionnaires, specific behavioral tasks, objective metrics) and a sufficient number of participants or experimental trials to support its conclusions?
- **QA3:** How central is the investigation of SRL control and/or embodiment to the study's main objectives, and to what extent do the findings contribute novel insights or methodologies to the broader field of human-robot interaction with supernumerary limbs?

This process resulted in a final selection of 18 core articles (all listed in Table 1) that are the basis for the synthesis and discussion presented in the following sections.

Based on these selected works, this review will first explore the fundamental concepts of SRLs, outlining their core principles, various design characteristics, and primary application domains (Section 2.2). It will then examine the various challenges and advancements in human-SRL interaction, with a particular emphasis on the spectrum of control strategies employed (Section 2.3.1) and the crucial aspect of user embodiment and experience (Section 2.4). Next, the integral role of eXtended Reality (XR) technologies, specifically VR and Mixed Reality (MR), as simulation and research tools in the SRL field will be explored (Section 2.5). The review will also briefly introduce collaborative robots (cobots) to contextualize a specific comparative gap in the existing literature relevant to this thesis (Section 2.6). Finally, this chapter will summarize the above findings, highlighting the current state-of-the-art, ongoing challenges, and specific research gaps that the present work aims to address (within Section 2.6).

Table 1: Summary of the 18 Core Articles Informing the Literature Review.

| **Ref** | **Title** | **Aspects Addressed** |
|---|---|---|
| [1] | *Human motor augmentation with an extra robotic arm without functional interference* | Control (HMI), Functional Interference, Learning |
| [9] | *Embodiment of supernumerary robotic limbs in virtual reality* | Embodiment (Peripersonal Space), VR Platform |
| [4] | *A virtual reality platform to evaluate the effects of supernumerary limbs' appearance* | Embodiment (Appearance), VR Platform |
| [5] | *Analysis and Observation of Behavioral Factors Contributing to Improvement of Embodiment to a Supernumerary Limb* | Embodiment (Behavioral Factors), Learning |
| [12] | *How long does it take to learn trimanual coordination?* | Control (Coordination), Learning |
| [14] | *Human Performance of Three Hands in Unimanual, Bimanual and Trimanual Tasks* | Control (Coordination, Performance) |

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**Table 1 – continued from previous page**

| Ref | Title | Aspects Addressed |
|---|---|---|
| [15] | *Redundancy Resolution in Trimanual vs. Bimanual Tracking Tasks* | Control (Redundancy, Coordination) |
| [13] | *Human Operation Augmentation through Wearable Robotic Limb Integrated with Mixed Reality Device* | Shared Autonomy, MR Application, Industrial Use |
| [2] | *A 3D head pointer: a manipulation method that enables the spatial position and posture for supernumerary robotic limbs* | Control (Head/Voice), VR Interface |
| [10] | *FaceDrive: Facial Expression Driven Operation to Control Virtual Supernumerary Robotic Arms* | Control (Facial Expressions), VR Interface |
| [8] | *Design and Assessment of Control Maps for Multi-Channel sEMG-Driven Prostheses and Supernumerary Limbs* | Control (Biosignals, sEMG) |
| [7] | *Computational Design of Personalized Wearable Robotic Limbs* | Design (Computational, Personalization) |
| [22] | *Social Digital Cyborgs: The Collaborative Design Process of JIZAI ARMS* | Design (Modular, Social), Embodiment |
| [11] | *Fake hands in action: embodiment and control of supernumerary limbs* | Embodiment (Ownership), Control |
| [6] | *Changing body ownership using visual metamorphosis* | Embodiment (Body Ownership, Visuals) |

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**Table 1 – continued from previous page**

| Ref | Title | Aspects Addressed |
|---|---|---|
| [18] | *The Supernumerary Hand Illusion in Augmented Reality* | Embodiment (Ownership), AR Application |
| [16] | *Remapping a Third Arm in Virtual Reality* | Control (Mapping), Embodiment, VR Interface |
| [3] | *A magnetic compatible supernumerary robotic finger for fMRI acquisitions* | Design (Specialized Hardware), Medical Applications |

## 2.2 Supernumerary Robotic Limbs: Defining the Paradigm

SRLs represent a quickly developing hot topic in the fields of robotics and human augmentation, introducing a new paradigm where humans can physically exceed their biological limitations through additional, wearable robotic limbs [1, 13, 14]. This section explores the foundational aspects of this paradigm. It will begin by establishing the core concepts that define SRLs and outline their primary goal of augmenting human capabilities. It will then seek to map what constitutes core features of SRLs, highlighting the varied forms these systems can take. Finally, this section will summarize the major application areas of the SRLs, and present its expected application prospects in multiple aspects. Understanding these fundamental elements is important for contextualizing the specific challenges and opportunities in SRL research, particularly in developing effective control strategies and enhancing user embodiment.

### 2.2.1 Core Concepts: Augmenting Human Capabilities

SRLs are wearable robotic systems fundamentally designed to enhance and extend innate human physical capabilities by providing users with additional, functional limbs [21]. While prosthetic devices try to replace the biological limb or give it the lost functionality, SRLs are by nature additive: they augment the existing human body with extra degrees of freedom (DOF) and effectors such as arms, legs or fingers [21]. The underlying idea is to extend the normal limits of motor ability in humans, so that people can do things that are currently difficult or impossible for an individual, or which require two or more people to do together [1, 21]. This augmentation can appear quite differently depending on the application, whether it's increased dexterity and mobility, or the ability to perform elaborate multitasking [21].

The main ambition of SRLs is to allow users to interact with their environment more effectively by expanding their physical reach, manipulation capacity or stability [21]. For example, an additional arm could enable a user to stabilize a workpiece while operating with natural hands for intricate assembly, or can provide support and tool manipulation for manufacturing or construction [13, 21]. the best-case scenario, the integration will allow users to perceive and control the SRL with enough intuitiveness that it will feel like a natural extension of their own body [9]. This seamless conection reduces the mental effort needed to use it, resulting in an operation with "cognitive transparency" [9]. This picture distinguishes SRLs from purely external robotic assistants or teleoperated systems and highlights a close cooperative relation between the human operator and its augmented capabilities. The successful implementation of this fundamental idea depends on effectively addressing major challenges in intuitive control while enhancing a strong sense of embodiment [1].

### 2.2.2 Design Variations and Classifications

There is a great diversity of design in the field of SRLs, which highlights the spectrum of the targeted usages and its continuous motivation in the research of human-robot collaboration. SRLs are often categorized from particular viewpoints such as "where the interface is physically attached to the human body", "SRL morphology", "the number of DOF" and "overall mechanical structure" [21]. A systematic review by Li identifies categories based on the number of extra limbs and their actuation or driven types, noting a prevalent focus on arm-like additions [21].

The point of attachment on the human body is a fundamental design choice that heavily impacts the SRL's workspace, stability and potential for ergonomic integration. Attachment areas typically described in the literature are the shoulders, back (most common on the lateral part), chest, or abdomen [21]. For instance, shoulder or back-mounted systems may offer a larger operational volume, while waist-mounted limbs might leverage the body's core for stability during manipulation tasks.

Morphologically, SRLs reside somewhere on a spectrum between highly anthropomorphic and completely non-anthropomorphic or tool-shaped [21]. Some designs aim to mimic human limbs, particularly arms and fingers, which may aid in intuitive control or enable a greater sense of embodiment by using existing human sensorimotor schemas. On the other hand, non-anthropomorphic designs, such as abstract manipulators or even cursor-like representations in virtual environments [2], prioritize functional optimization for specific tasks over biological resemblance. This exploration of "dissimilar" avatars that diverge from the human form is a significant area of research, investigating how such augmentations can lead to new abilities and perceptions of the self [24]. One example is the "JIZAI ARMS" project, which focuses on modular and reconfigurable robotic limbs, representing an outlook of adaptable and potentially socially interactive augmentation instead of predetermined morphologies [22]. This relates to the increasing interest in computational design and the personalization of SRLs, aiming to customize their shape and function for individual users and specific contexts.

The DOF offered by an SRL influences its dexterity and manipulative capabilities, but also increases control complexity. Designs range from simple single-DOF assistive devices to multi-DOF arms capable of complex motions [21]. The SRL mechanical design, such as actuator type, strength, and integrity, is all important as well, as demonstrated by Abadian, who introduced a computational method to personalize SRL design by optimizing factors like link lengths and actuator placement to create lightweight and user-specific limbs [7]. Additionally, highly specialized SRLs are being developed for unique operational environments, such as the fMRI-compatible supernumerary robotic finger designed by Hussain, that have strict constraints on materials and electromagnetic interference [3]. The observed design aspects illustrate the diversity of the SRL ecosystem and have a significant impact on the control strategies and the UX.

### 2.2.3 Key Application Areas and Potential

The diverse designs and augmenting capabilities of SRLs translate into a spectrum of potential application areas, ranging from industrial settings to healthcare and specialized operational environments [21]. The great potential lies in allowing individuals to perform tasks more efficiently, safely or with capabilities exceeding their natural reach. The review by Li drafts prospective applications in fields such as manufacturing, construction, medicine, service industries, disaster relief and defense, highlighting the wide-ranging impact SRLs could have [21].

In the industry and manufacturing domain, SRLs offer the promise of augmenting human workers in complex assembly, maintenance or logistic tasks [13, 21]. For instance, Jing explored the use of a wearable robotic limb integrated with an MR device to assist in typical aircraft manufacturing tasks like cable installation and electrical connector soldering, demonstrating potential improvements in task completion time [13]. SRLs could also be used for lifting heavy objects, stabilizing tools or enabling workers to manage multiple components simultaneously, thus improving productivity and potentially reducing musculoskeletal fatigue and workplace injuries [21, 28].

The healthcare and rehabilitation field offers another important opportunity for the application of SRLs [21]. They could act as advanced assistive devices for individuals with motor impairments, providing support for daily activities or enabling new levels of independence. There is also potential for SRLs in medical procedures, perhaps assisting surgeons by holding instruments or providing additional stable manipulation points. Specialized SRLs, like the fMRI-compatible robotic finger developed by Hussain, demonstrate the potential for use in medical research and diagnostic settings, allowing for human-robot interaction studies within restrictive imaging environments [3].

Outside of the sectors described, a number of day-to-day tasks and niche operations could also benefit from SRLs. This could range from simple assistance in domestic duties to enabling individuals to perform more complex tasks that require more than two hands [21]. As the technology evolves, applications in demanding environments such as space exploration, as suggested by Ballesteros in the context of next-generation spacesuit technology [35,36] or in search and rescue operations [21], may also become viable. However, the realization of this broad potential is intrinsically linked to advancements in intuitive control systems [1] and the successful increase of user embodiment [9], which remain active areas of research.

## 2.3 Fundamental Challenges in SRL Control

Intuitive and efficient sophisticated limb control is essentially the limiting factor in the performance of SRLs [21]. While SRLs offer the potential to expand human capabilities by introducing extra DOF, this same addition presents substantial control challenges [1]. The human brain relies on available DOFs to control an equivalent number of DOFs in external tools or systems [15]. However, wearable SRLs introduce "unnatural" DOFs that must be managed without compromising the user's innate motor capabilities [1]. This often leads to significant difficulties, as users must learn to coordinate these new limbs simultaneously with their biological ones, a task which previous studies have highlighted as inherently complex [12,14,20].

A primary problem is the potential for increased cognitive load [1]. If the control scheme is not intuitive or demands excessive conscious effort, the mental load can negate the physical benefits of the extra limbs, hindering task performance and user adoption [21]. The work by Dominijanni specifically addresses the challenge of allowing users to proficiently control extra robotic arms (XRAs) without hindering their existing functions, such as speaking or visual exploration, the community refers to it as the problem of "functional interference" [1]. Finding a control strategy that feels natural and allows for seamless collaboration between the user and the SRL system is therefore essential. This requires careful consideration of how control inputs are mapped and how much autonomy, if any, is given to the SRL itself. In addition, the guarantee of the SRL's safety and precision of motion when working in cluttered and complex scenarios, such as confining environments, is a constant engineering challenge that is directly connected with the effectiveness of the control system [28]. Overcoming these fundamental control challenges is a critical step towards realizing the full potential of SRLs as functional extensions of the human body.

### 2.3.1 A Spectrum of Control Interfaces

To address the fundamental challenges of intuitively controlling SRLs, researchers have explored a variety of human-machine interfaces (HMIs). Again, these interfaces range from the type of input they typify to their complexity, and the extent to which they take advantage of pre-existing human motor behavior or non-occupied sensory-motor channels. In general, one would like to find mappings that are easy to learn, require as little mental load as possible, and do not interfere with the user's natural limbs, as highlighted by Dominijanni [1].

A major category is, for example, body mapping and kinematic control, in which the movement of present body parts is translated to control SRL. This involves using movements from residual limbs to assist with tasks or using motion from limbs or body parts that are less active. Foot-based controls, for example, have been explored in several studies as a mean to operate extra limbs, using the dexterity of the lower extremities [12, 14, 21]. More specific examples include head-based interfaces; Oh introduced a "3D head pointer" that combines head pointing with voice recognition to manipulate the position and orientation of a wearable robotic arm, tested on a VR use case [2]. Similarly, Dominijanni developed and assessed a multimodal motor HMI that integrates gaze detection with diaphragmatic respiration to control an extra virtual arm, demonstrating that this approach can be used independently of or in coordination with biological arms without functional interference [1].

Biosignal-driven control represents another central solution, aiming to interpret physiological signals directly for SRL command. Surface electromyography (sEMG) is a frequently investigated modality, where electrical activity from muscle contractions is decoded. Maimeri focused on the design and assessment of control maps for multi-channel sEMG to drive both prostheses and supernumerary limbs, highlighting the importance of effective mapping for intuitive control [8]. While powerful, sEMG interfaces often require careful calibration, can be susceptible to issues like muscle fatigue or changes in electrode contact and are highly sensitive to noise [8].

Researchers are also exploring alternative input channels to free up the user's hands and primary motor functions. Voice commands are commonly integrated, often for discrete actions like mode switching or grasp commands, as seen in the work by Oh [2] and employed by Jing via the HoloLens2 for human-robot interaction with an SRL [13]. Facial expressions have also been investigated as a control modality; Fukuoka designed "FaceDrive," a system using optical sensors within an HMD to interpret facial expressions for commanding virtual supernumerary robotic arms, exploring mappings between expressions and actions like grabbing or extending the arms [10].

The choice and design of a control interface are deeply linked with the specific characteristics of the SRL, the nature of the tasks it is intended to perform, and the desired balance between direct user control and potential shared autonomy [21].

### 2.3.2 Advancing SRL Utility: Shared Autonomy, Learning, and Coordination

Beyond the development of diverse direct control interfaces, advancing the utility and practicality of SRLs increasingly involves exploring concepts of shared autonomy and understanding the complexities of human learning and coordination with these additional effectors [21]. The vision is evolving from SRLs as passively controlled tools to more cooperative systems that can intelligently assist the user and adapt to their needs, as well as systems that users can become proficient with over time [1,13].

The concept of shared autonomy and collaborative control positions the SRL as a proactive partner instead of just an extension that is solely operated. This method helps reduce the mental and physical effort required from the user. It allows the SRL to make some decisions and perform actions on its own [13]. For example, Jing proposed a system where the SRL is triggered by user keywords and then autonomously estimates holding positions and executes grasping actions, thus augmenting human operations in manufacturing tasks [13]. This concept of a collaborative "companion" SRL that works alongside the user, rather than being completely under their direct control for every small movement, represents a meaningful direction. Such systems might rely on gesture recognition, voice triggers, or context awareness to initiate pre-programmed or adaptive assistive behaviors, allowing the user to focus on higher-level task goals.

Advancements in autonomy are linked to human learning, adaptation, and coordination. Operating additional limbs effectively is not typically an innate skill and often requires considerable practice [1, 12, 14]. Research has begun to quantify this learning process; for instance, studies by Allemang-Trivalle have investigated the timeframes and mechanisms involved in learning trimanual coordination [12]. Similarly, work by Huang has focused on evaluating human performance in tasks requiring three-handed coordination, exploring the challenges and capabilities associated with managing multiple effectors [14, 20]. Dominijanni also noted significant performance improvements with daily training and learning retention in their study of an extra virtual arm [1]. Understanding how users learn to resolve redundancy and develop new motor collaboration is crucial for designing SRLs and training protocols that facilitate faster adaptation and higher levels of proficiency [15]. This learning process may also play a role in shaping the user's sense of embodiment with the additional limbs [5].

Together, progress in shared autonomy and a deeper understanding of human learning and multi-limb coordination are essential for transforming SRLs from complex novelties into truly effective and seamlessly integrated tools for human augmentation [21].

## 2.4 Embodiment and User Experience with SRLs

Despite the technical aspects of control, the successful integration of SRLs is strongly influenced by the user's subjective experience, specifically the phenomenon of embodiment. For an SRL to become an effective extension of the self, users should perceive it not just as an external tool, but as an actual part of their own body. This sense of embodiment is considered crucial for intuitive operation, reducing cognitive load and ultimately enhancing the overall UX and acceptance of the augmentation. This section will investigate the theoretical foundations of embodiment, explore the various factors known to modulate this experience in the context of SRLs, and discuss the methodologies employed to assess both the sense of embodiment and other key aspects of UX when interacting with these robotic systems.

### 2.4.1 Theoretical Foundations: Body Ownership, Agency, and Self-Location

The subjective experience of embodiment with an SRL is a complex construct that goes beyond sole physical attachment. Foundational research in cognitive science and neuroprosthetics identifies several key components that contribute to the feeling of an artificial limb being part of one's own body [25]. Three central pillars in the theoretical understanding of embodiment are the sense of body ownership, the sense of agency, and the experience of self-location [25].

The sense of body ownership refers to the pre-reflective feeling that a particular limb or body part, whether biological or artificial, belongs to oneself [25]. Studies have explored how this sense can be induced for artificial limbs, often using congruent multisensory feedback [6, 18]. For instance, Sasaki investigated how visual metamorphosis can alter body ownership perception [6], while research on illusions like the "supernumerary hand illusion" in augmented reality demonstrates that ownership can indeed be produced over a virtual arm even in the presence of one's real limbs [18]. Newport also explored the embodiment of "fake hands", linking it to control aspects [11]. Understanding the mechanisms that support ownership is crucial for designing SRLs that users can readily accept as part of their extended phenotype.

Different from ownership is the feeling of agency [25]. This is the sense of being the one who initiates and controls actions and what results from them. In the context of SRLs, agency refers to the user's experience of intentionally commanding the supernumerary limb's movements and producing desired effects in the environment. A strong sense of agency is essential for effective and intuitive SRL operation, as it supports the feeling of mastery over the augmented body part [11]. The transparency and responsiveness of the control interface play a significant role in defining this experience.

Finally, self-location refers to the spatial experience of where one perceives oneself to be, often centered within the physical boundaries of their body [25]. SRLs, especially those that reach into personal space or stand out visually, can change how we feel about our sense of where we are. For example, Arai investigated whether the perception of peripersonal space changes with the use of an SRL in a virtual environment, suggesting that embodiment can lead to functional alterations in spatial perception [9].

These three components (ownership, agency, and self-location) are often connected and contribute to the overall success of human-SRL integration. Inducing strong feelings of ownership and agency over an SRL, while maintaining a coherent sense of self-location, are key objectives in developing truly embodied robotic augmentation.

### 2.4.2 Factors Modulating the Embodiment of SRLs

The extent to which a user embodies SRLs is not only an inherent characteristic of the technology, but is largely influenced by a combination of design features, interaction dynamics and user-specific components [21]. Understanding these factors is necessary for creating SRLs that feel like natural extensions of the body. Key among these are the limb's visual and morphological properties, the nature and timing of multisensory feedback, the characteristics of the control interface and the context of the task being performed.

Visual and morphological characteristics play a substantial role in shaping embodiment. The appearance of the SRL can influence how readily a user accepts it as part of their body schema. Jiang specifically developed a virtual reality platform to evaluate the effects of supernumerary limbs' appearance on user perception, indicating the importance of visual design choices [4]. Whether a limb is designed to be humanoid or takes on a more abstract, tool-like form can impact user expectations and the ease of integration into their body image [19]. Research on "dissimilar" avatars that intentionally deviate from a realistic human form suggests that such augmentations can alter the user's perception of their own capabilities and their relationship with the virtual body, which is a key aspect of the embodiment experience [24].

Congruent visual feedback, where the SRL moves as intended and in synchrony with the user's commands, is very important [18]. This is frequently reinforced by other sensory forms. For example, studies by Arai examined visuotactile crossmodal congruence during SRL embodiment [9], and Rosa showed that embodiment is affected by both perceptual visual-tactile synchrony and motor synchrony between virtual and real limbs [18]. Nishida studied how behavioral cues help improve feelings of embodiment [5]. Their research likely looked at how feedback and interaction play a role in this process. While haptic feedback is often considered important, its optimal implementation can be complex; Dominijanni, for example, observed no further performance improvements with artificial haptic feedback in their specific setup, suggesting that the necessity and type of feedback may be context-dependent [1].

The design of the control interface and its relevance to the task also critically influence embodiment, primarily through its impact on the sense of agency. An intuitive, responsive control scheme that provides a clear mapping between user intent and SRL action encourages a stronger sense of control and, by extension, embodiment [1]. On the other hand, cognitively demanding interfaces can create a feeling of disconnection. The perceived utility and effectiveness of the SRL in completing a given task can either enhance or reduce the embodiment experience.

Finally, factors such as prolonged exposure, training and individual user differences (prior experience with VR or robotics, spatial abilities or even susceptibility to illusions) can also change the level of embodiment reached. The process of learning to use an SRL effectively may itself contribute to a stronger integration of the limb into the user's body representation over time [1, 5, 12]. Optimizing these factors is a key challenge in the design of truly integrated and intuitive SRL systems.

### 2.4.3 Methodologies for Assessing Embodiment and User Experience

Quantifying the inherently subjective constructs of embodiment and overall UX with SRLs necessitates a multi-method approach, combining explicit self-reports with implicit behavioral and physiological observations [29]. These methodologies aim to capture different aspects of how users perceive and interact with their augmented capabilities.

Subjective self-report measures, predominantly questionnaires, are widely utilized to measure users' feelings of body ownership, agency, and self-location [25]. These often utilize Likert scales to rate agreement with statements about the embodiment experience. Standardized questionnaires are also used to assess related aspects of UX, such as perceived workload (NASA-TLX), presence in virtual environments, and usability [23, 29]. For example, Arai used a questionnaire to directly ask participants whether they regarded the extra limb as part of their own body [9].

Behavioral measures offer more objective insights into how SRL use might alter perception and action. These can include performance metrics on specific tasks (speed, accuracy, error rates, etc.), which may indirectly reflect the ease of control and integration of the SRL [29]. More targeted behavioral paradigms include visuotactile crossmodal congruency tasks, which assess changes in peripersonal space representation as an indicator of embodiment [9] and adaptations of proprioceptive drift tasks traditionally used in studies like the Rubber Hand Illusion [11, 17]. Observing behavioral factors that contribute to improvements in embodiment over time is also a key approach [5].

Physiological measures can provide complementary data, attempting to capture unconscious responses associated with embodiment or stress. Techniques such as skin conductance response (SCR) have been explored, for example by Rosa, to detect arousal changes in response to events concerning the artificial limb, although the significance and interpretation of such measures can vary [18]. While more complex to implement, these can offer a window into more implicit aspects of the user's experience.

Often, a combination of these subjective, behavioral and physiological methodologies provides the most comprehensive understanding of SRL embodiment and the overall UX, allowing researchers to correlate explicit feelings with observable changes in perception and physiology [29].

## 2.5 Virtual and Mixed Reality in SRL Research

The investigation of complex human-robot systems like SRLs, particularly aspects concerning novel control schemes and subjective UXs such as embodiment, greatly benefits from advanced research methodologies and tools. In this context, XR technologies, especially VR and MR, have become increasingly necessary to the study and development of SRLs. These immersive platforms offer unique capabilities for simulating interactions, testing designs and evaluating user performance in controlled but realistic settings. This section will explore the specific advantages that VR and MR bring to SRL research and showcase representative examples of how these technologies are being applied to advance the field.

### 2.5.1 Advantages of VR for Simulating and Evaluating SRLs

The adoption of XR technologies, particularly VR, in SRL research derives from several distinct advantages these platforms offer for simulation and evaluation. Firstly, VR environments provide an excellent margin of safety for both users and equipment, allowing researchers to test novel, complex, or potentially hazardous control schemes and SRL behaviors without the risks associated with physical prototypes [28]. This is very important in early-stage development or when exploring unconventional human-robot interactions.

Secondly, VR significantly enhances cost-effectiveness and the speed of iterative development. By reducing the immediate need for fabricating and modifying physical hardware for each design change or experimental condition, researchers can rapidly prototype, test, and refine SRL concepts, control interfaces, and task scenarios [1,4]. This accelerated iteration cycle is extremely important in a field with many open design questions. Associated with this is the advantage of experimental control and replicability; VR allows for the precise manipulation of virtual environments and task parameters, ensuring consistency across different participants and study phases, which is often challenging to achieve with physical setups [29].

Furthermore, the inherent flexibility and modularity of platforms like UE5 enable researchers to easily implement and switch between various SRL models, control logic and interactive elements, encouraging comparative studies and adaptation to diverse research questions [4]. VR is also able to create engaging and environmentally relevant experiences. High-fidelity visual and audio stimuli, combined with interactive physics, can produce realistic user responses and a strong sense of presence, which are particularly important for investigating embodiment and cognitive workload [9, 25]. Finally, these virtual environments often facilitate rich data capture, allowing for detailed logging of user movements, SRL kinematics, task performance metrics and interaction events, which are very important for quantitative analysis [1]. These collective advantages position VR as an essential tool for advancing the understanding and development of effective SRL systems.

### 2.5.2 Representative XR Platforms and Applications in SRL Studies

The utility of XR is evident in numerous studies that have developed and utilized custom VR and MR environments to investigate specific aspects of SRL interaction [29]. These applications showcase how XR enables focused research into control, embodiment, and task performance.

VR has been instrumental in the development and assessment of novel control interfaces. Oh employed a fully immersive VR environment to evaluate the accuracy and efficiency of their "3D head pointer" system for SRL manipulation [2]. Similarly, Fukuoka utilized VR to investigate mappings between facial expressions and SRL commands with their "FaceDrive" system [10]. Dominijanni also made use of a sophisticated VR platform, integrated with an exoskeleton, to test a human-machine interface based on gaze and respiration for controlling an extra virtual arm [1].

XR environments are also key for conducting studies on SRL embodiment. Arai developed an SRL system that can be used within VR to explicitly evaluate whether an extra limb could be embodied [9]. Jiang created a VR platform specifically to assess how variations in the visual appearance of supernumerary limbs affect user perception and acceptance [4]. The capacity of VR to manipulate visual feedback and limb representation, as seen in studies on remapping a third arm, is essential for such investigations [16].

XR is also applied to evaluate task performance and interaction safety [14, 28]. The use of virtual environments is a key methodology for assessing and mitigating risks related to HMI safety before physical deployment [28]. In the domain of MR, Jing demonstrated the integration of a HoloLens2 device with a wearable robotic limb to augment human operations in realistic manufacturing tasks, using MR to provide an intuitive communication bridge [13]. These examples underscore the versatility of XR in creating custom experimental setups to address diverse and complex questions within SRL research, facilitating investigations that would be significantly more challenging or resource-intensive with purely physical systems.

## 2.6 Literature Synthesis, Contextual Gaps, and Thesis Positioning

The previous sections have explored the complex landscape of SRL research, highlighting fundamental concepts, various designs, control strategies, embodiment factors and the crucial role of XR in their development. This final section now aims to synthesize these various topics to provide a clear overview of the current state-of-the-art and the persistent challenges within the field. It will also introduce collaborative robots (cobots) as an important, yet under-explored, comparative context for SRLs, highlighting a specific research gap. Ultimately, this synthesis will serve to precisely position the current thesis, stating the specific research gaps it seeks to address and the contributions it intends to make to the ongoing advancement of human augmentation technologies.

### 2.6.1 Current State-of-the-Art and Persistent Challenges in SRL Research

The reviewed literature reveals a dynamic and rapidly evolving field in SRL research, characterized by significant advancements in conceptualization, design and interaction metodologies [21]. The current state-of-the-art demonstrates a growing improvement in SRL designs, ranging from personalized, computationally derived forms [7] to modular [22] and non-anthropomorphic structures [19], alongside a diverse exploration of potential applications. A diverse range of control interfaces has been explored, utilizing different human input channels [21]. These include direct body movements [2], biosignals [8], and innovative modalities like facial expressions [10]. There has also been initial exploration into shared autonomy [13] and an increasing understanding of how humans learn to coordinate movements with multiple limbs [12]. The understanding of embodiment has also matured, with established theoretical components like body ownership and agency being actively investigated, alongside factors that modulate this experience and methodologies for its assessment, often within XR environments [9].

Despite this progress, several challenges continue to define the boundaries of SRL R&D. Achieving intuitive and effective control that minimizes cognitive load while enabling complex manipulation remains a primary obstacle [1]. While many interfaces show promise, a "one-size-fits-all" solution is unfeasible and the seamless integration of user intent with SRL action without functional interference is an ongoing goal [1]. While factors influencing embodiment are increasingly understood, consistently inducing a robust and stable sense of ownership and agency across diverse users, SRL designs and task contexts is still a significant challenge [4, 5]. The practical viability and real-world integration of SRLs also pose substantial limitations, including aspects of ergonomics, power, reliability and social acceptability, which are less explored in controlled lab settings [21, 22]. Finally, as highlighted by the need for platforms like the one developed in this thesis, a broader challenge is the standardization of evaluation methodologies, including common tasks, metrics and benchmarked platforms, which would enable more direct comparison between different SRL systems and control strategies emerging from various research groups [29]. Addressing these challenges is essential for translating the potential of SRLs into real human augmentation.

### 2.6.2 Collaborative Robots (Cobots) as a Comparative Context

Parallel to the development of wearable SRLs, another significant advancement in human-robot interaction for assistance and productivity is the emergence of collaborative robots, or "cobots". Cobots are designed specifically to operate safely alongside humans in a shared workspace, often assisting with tasks in manufacturing, assembly, and logistics. Unlike SRLs, which are intimately worn with the goal of integrating into the user's body schema, cobots function as external partners. They are typically stationary or mobile and their collaboration model involves task-sharing or sequential work, where the human and cobot perform complementary actions on a workpiece.

Although both technologies aim to augment human capability, a review of the literature reveals a notable gap: direct empirical comparisons between these two distinct modalities are scarce. While research into cobot usability and safety is extensive, very few studies evaluate how user performance, cognitive workload or the sense of embodiment differ when a task is performed with a wearable SRL versus an external cobot. This comparative gap is significant because these two approaches to human augmentation offer fundamentally different interaction experiences and have different implications for physical and cognitive integration. Understanding these differences is crucial for determining the most appropriate assistive robotic solution for various tasks and user needs. This comparative gap provides a key motivation for one of the experimental investigations in this thesis, which directly puts an autonomous SRL against an autonomous cobot in a shared assembly scenario.

### 2.6.3 Overall Research Gaps and Contributions of This Thesis

The primary research gaps identified are: (1) the lack of standardized, modular VR platforms for systematic and comparative evaluation; (2) the scarcity of direct empirical comparisons between wearable SRLs and external cobots for collaborative tasks; and (3) the need for continued refinement of control strategies and a deeper understanding of embodiment.

This thesis is positioned to directly address these gaps through several key contributions:

- **A Novel Methodological Tool:** The primary contribution is the development of a novel, modular VR environment in UE5. This platform provides an accessible and adaptable testbed for the systematic and safe exploration of diverse SRL control interfaces and their impact on user embodiment.

- **Novel Empirical Data:** This work provides the first direct empirical comparison between an autonomous wearable SRL and an autonomous external cobot in a shared assembly task. The findings on user performance, workload and subjective experience contribute valuable data to a significant gap in the human-robot interaction literature.

- **Foundational Insights for Future Work:** By implementing and studying various SRL operational modes, this thesis offers initial insights into their practical application. It lays the groundwork for more extensive future assessments of specific control methods and provides a robust platform to simplify the testing and evaluation of current and future embodiment theories.

Collectively, these contributions are intended to advance both the methodological tools for SRL study and the empirical knowledge of how humans interact with these emerging augmentation technologies.

# Chapter 3

# Methodology

This chapter will explain the methods to build the virtual environment and SRL interactions analysis.

## 3.1 Research Design

This chapter describes the general methodological framework used in this work for the study of efficacy and user experience of SRL systems. The research employs an experimental approach, centered around the development and use of a custom-built VR environment created in UE5. The design focuses on iterative development of interactive scenarios, defines experimental conditions for comparative analysis and outlines a strategy for data collection to evaluate user performance and gather subjective feedback. The following subsections will elaborate on the specifics of the VR scenario development, the design of the experimental tasks, the configuration of the experimental conditions and the overall structure of the user studies conducted.

### 3.1.1 VR Scenario Development Using Unreal Engine 5

An imperative for this research was the development of a custom VR environment specifically designed to simulate and evaluate SRL interactions during assembly tasks. UE5 was selected as the development platform due to its advanced capabilities in rendering high-fidelity graphics, its robust physics engine, which is crucial for realistic object interactions, native OpenXR support for broad hardware compatibility, and its Blueprints visual scripting system (advantages discussed in

Section 1.1.4).

The core of the simulation is a VR Pawn representing the user, equipped with controllable virtual representations of their own hands and the attachable SRLs.

Much work went into implementing realistic interaction mechanics. This included an ad-hoc physics-based collision handling system to ensure accurate and believable interactions between the user's virtual limbs (both natural and supernumerary), objects and the environment. Custom procedural hand-grab logic was developed to provide a natural and responsive representation of grasping and manipulating objects. Specific mechanics around attaching objects together (like literally snapping parts together and ensuring alignment) were implemented in great detail to also solve issues such as physics inheritance (so parts wouldn't just fall apart) and visual coherence for things to look like they belong together. The environment also includes functional virtual tools (hammer, screwdriver, allen key) which have their own interaction logic and are necessary for assembly processes.

The SRLs themselves were designed to be modular components that could be virtually attached to the user's pawn. Their movement capabilities were realized through implemented control schemes, including Inverse Kinematics (IK) for more natural arm movements. The environment features distinct task areas with all necessary components, fasteners and tools readily available, with features like fastener trays to simplify the grabbing of smaller items, especially during autonomous SRL operation. The approach emphasized modularity, where different SRL control inputs (direct VR controller input for manual modes) and autonomous behaviors (specified through a developed Task Manager and Finite State Machine (FSM)) could be easily integrated and tested. This iterative development process aimed to create a robust, realistic and flexible testing environment capable of supporting the specific experimental objectives of this thesis.

### 3.1.2 VR Pawn and SRL Representation

Central to the VR simulation is the "VR Pawn", which serves as the user's embodied avatar within the Unreal Engine 5 environment (Figure 1). This Pawn is set up to provide a first-person perspective, incorporating a camera system that follows the user's head movements as tracked by the VR HMD. Attached to the Pawn are virtual representations of the user's own hands and arms, directly mapped to their real-world movements via the VR controllers. These "real arms" are equipped with interaction logic, including a "Grabber" component, enabling the user to directly manipulate objects and tools within the environment.

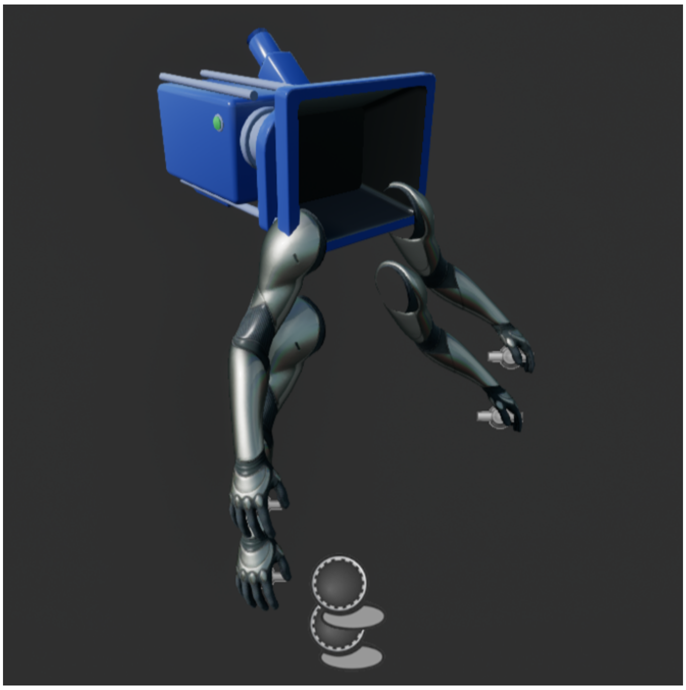


Figure 1: The VR Pawn used in the experiment, as seen in the Unreal Engine 5 editor. The attached components for the user's head, hands, and the supernumerary robotic limbs are visible.

The SRLs are conceptualized and implemented as additional "extra arms" or "effectors" that are also attached to this central VR Pawn. They are equipped with a "Camera Follower" component that simulates the attachment to the wearer's body, since not all VR systems are equipped with body tracking. Conceptually, for the experiments conducted, these SRLs are designed with a human-like visual appearance to facilitate a potentially more natural user experience and to allow for direct comparison with the user's own virtual limbs. The underlying system was developed to be modular, allowing for the future integration and exploration of alternative, even non-anthropomorphic SRL designs if required. Like the user's "real" virtual arms, the SRLs are also equipped with "Grabber" components, enabling them to interact with and manipulate objects in the environment under their specific control schemas. Their movement is handled by the implemented control strategies, utilizing the built-in IK to achieve more natural and plausible arm motions.

### 3.1.3 Object Interaction and Assembly Mechanics

A high-fidelity interactivity and assembly mechanic pipeline was created in VR in order to serve realistic and purposeful assembly tasks. The virtual components of the furniture, or meshes, were created in Blender or sourced from external libraries. These components were designed to be assembled into a final object, requiring a robust system for handling parts, tools, and their connections.

The core attachment mechanic for joining parts relies on a system of box collisions and pre-placed, hidden meshes that become visible once successfully attached. Once a user gets a component near where it should be placed on the main frame, it can snap along an alignment axis, making clear the user is close to its correct position. This system was designed to be reversible (within the alignment process), allowing parts to be detached if needed before attachment confirmation. A significant challenge in development was ensuring correct part alignment without disrupting the physics simulation. Early attempts using scene components for directional guidance were found to disrupt physics inheritance. This was solved by making all assemblable meshes inherit physics directly from a root object and using relative transforms to manage alignment. To prevent a visual disconnect where the user's hand would drift away from an object during alignment, the hand's location is smoothly interpolated (lerped) to the correct position on the object using a weighted falloff function, ensuring the user feels a continuous grasp.

A set of virtual tools with distinct interaction logic was implemented to complete the assembly. This includes a hammer, a screwdriver and an allen key. The hammer's logic is based on free motion, where a sufficiently forceful hit on a dowel pin confirms its attachment. The screwdriver and Allen key utilize physics constraints that fix the tool's head in place on a screw while allowing only the necessary rotational motion to tighten it. To manage the progress of these connections, a "Fastener Manager" component was added to track the insertion progress of each screw or dowel.

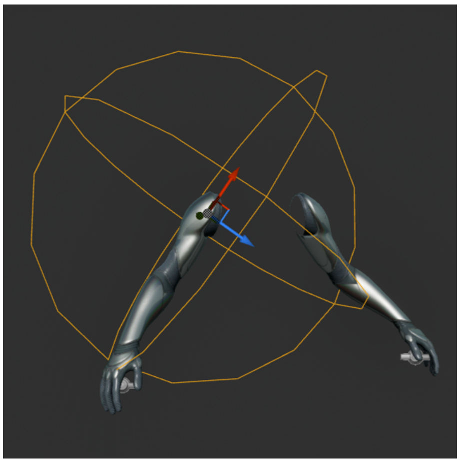
Lastly, various auxiliary functionalities were implemented to improve the overall user experience. This includes a custom procedural hand-grab logic for natural object interaction and a system to automatically respawn dropped objects at their original location, preventing runs from being aborted due to accidental drops. This comprehensive system of mechanics provides a functional and robust framework for conducting the assembly experiments.

### 3.1.4 Implemented Control Modes

The ability of the platform to be used as a general testing enviroment was demonstrated by implementing different modes of control. These modes span a spectrum from direct manual control of the SRLs to high-level commanding of autonomous behaviors and enable the exploration of various interaction paradigms in the future.

**Manual Control Modes** Three unique manual control designs were developed to enable direct user control of the SRL:

- *Polar Coordinate Control*: This initial mode has been introduced mainly for system testing purposes and is not suggested as a good alternative for control of the system. It offers direct effector control by mapping the VR controller's thumbstick to the angle and face buttons (A/B - X/Y) to the radius of the SRL's position relative to its base on each shoulder. This allows for deliberate and precise positioning of the SRL in a dynamic 2D plane. (Figure 2)
- *Mirroring*: This mode offers a direct and intuitive mapping where the SRL's movements are a one-to-one kinematic reflection of the user's real arm movements. This allows the user to leverage their natural proprioception to guide the SRL. The mode is typically turned on and off by a button press or a voice command.
- *Retargeting*: Distinct from simple mirroring, this is an advanced form of guided manual control based on the "virtual fixture" concept proposed by Kawamura



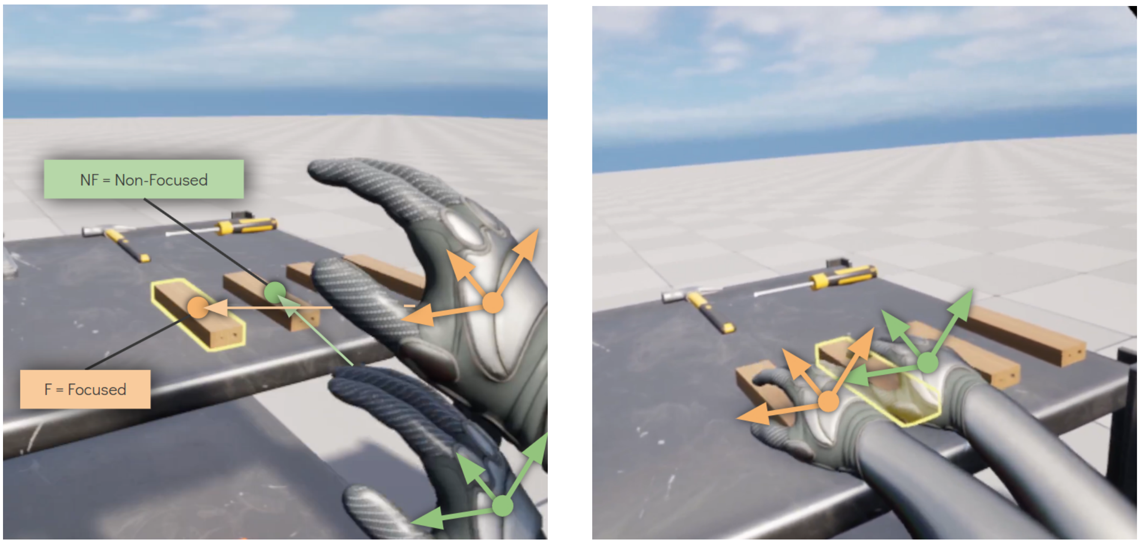
(a) Visualization of the dynamic 2D plane (sphere) in which the SRL end effector moves for the Polar Coordinate Control mode.

(b) Left controller mapping: thumbstick controls the polar angle.

(c) Right controller mapping: face buttons (A/B or X/Y) control the radius.

Figure 2: Visual overview of the Polar Coordinate Control inputs for the SRLs.

in their SyncArms system [26] (Figure 3). The goal is to enable parallel manipulation of two robotic arms—one in a "Focused" (F) environment that the user is looking at, and another in a "Non-Focused" (NF) environment. In the case of this thesis, we will have 2 sets of "Focused" and "Non-Focused" environments. The system's behavior is dependent on the gripper's state. When the gripper is open, the control assists the user by ensuring the NF arm maintains the same spatial relationship to its target as the F arm does to its target. The target position for the NF arm's end-effector ($P_{NF}$) is calculated using the F arm's position ($P_F$) and the translation vectors from each arm's base to their respective target objects ($T_F^i$ and $T_{NF}^i$). The formula used is: $P_{NF} = P_F - T_F^i + T_{NF}^i$. When the gripper is closed (for example, after grasping an object), this assistive offset is removed, and the arms operate in complete synchronization ($P_{NF} = P_F$). This allows the user to place objects with the same relative positioning in both environments. The assistance is applied implicitly; the corrective offset is added gradually, proportional to the user's own hand movements, to prevent abrupt motions in the peripheral vision that could reduce the user's sense of embodiment.




(a) Retargeting assistance initiated. The user's hands (leader) and the SRLs (follower) start at different relative positions to their respective targets.

(b) Targets reached. The system has applied a corrective offset to ensure the SRLs arrive at their targets with the same spatial relationship as the user's hands.

Figure 3: Visualization of the Retargeting control mode, showing the initial state (a) and the corrected final state (b) after the assistive offset is applied.

**Autonomous Modes** To explore collaborative interactions, the environment supports autonomous SRL behaviors that are directed by high-level user inputs rather than continuous manual control:

- *FSM-Based Autonomy*: For the structured assembly tasks, an FSM was developed to manage the SRLs' autonomous actions. The FSM executes predefined, multi-step action sequences, such as the "Reach-Grab-Bring Sequence", which commands the SRL to retrieve a required part or tool and to bring it to a convenient hand-off location for the user. This allows the SRL to act as a proactive assistant, anticipating the user's needs based on the assembly workflow.

- *User-Commanded Autonomous Actions (Gaze and Voice)*: As a separate paradigm, the system also supports on-demand, user-initiated autonomous actions. In this shared-control mode, Gaze and Voice commands are paired to initiate a discrete autonomous sequence. To select a target, the user gazes at an object, which is a highlight in the environment using head-based sphere trace. A voice command "pick up" is then issued. This combination of inputs begins an automated "Reach-Grab-Bring Sequence" where the SRL catches and retrieves from a peripheral location, the object requested by the user. This mode is distinct from the sequential FSM, offering a reactive form of assistance where the user remains in command of the overall workflow.

### 3.1.5 Experimental Task Design

The experimental design was based around a single challenging, multi-step assembly task designed to be sufficiently demanding to benefit from robotic assistance and to provide rich data for evaluation. The task chosen for all experimental conditions was the assembly of a virtual stool. This specific task was selected for its not-too-complex nature, but still requires users to manage multiple components and fasteners, utilize a variety of virtual tools (hammer, screwdriver, Allen key) and perform precise actions involving part alignment and attachment. Using a single, standardized task for all participants and conditions ensures that performance and experience data can be compared directly, avoiding any potential confounding variables that could arise from using different tasks.

While the formal evaluation is focused on the stool assembly, the underlying VR platform was engineered for modularity, demonstrating its capability as a flexible testing environment. Other complex assembly tasks, such as the construction of a step-stool, were also fully implemented and are available within the environment. This modular design, which separates the interaction logic from the specific task assets, allows for new assembly scenarios to be created and integrated with relative simplicity. To guide participants through the required procedure, a dynamic instruction manual was included in the virtual environment, which visually presents the necessary steps for the current stage of the assembly. This combination of a standardized primary task and a flexible underlying framework provides a robust and replicable setting for rigorously evaluating user performance and experience across the different assistance conditions.

## 3.2 Equipment and Setup

All experiments were conducted using a specific configuration of VR hardware. The setup was designed to provide participants with a stable, immersive and interactive VR experience, ensuring that the focus of the evaluation remained on the task performance and subjective experience with the SRL systems rather than the technical limitations of the equipment. The following sections detail the specific hardware and software components utilized in this research.

### 3.2.1 Hardware and Software

The experimental platform was built using a combination of consumer-grade VR hardware and a powerful software development environment extended with specialized plugins.

**Hardware:**

- *VR System*: The primary hardware consisted of a Meta Quest 3 headset and its two accompanying Touch Plus controllers (Figure 4). This system was chosen for its high-resolution display and robust inside-out tracking, which provides an immersive user experience.
- *Personal Computer (PC)*: A high-performance Windows-based Laptop PC was used to run the simulation. The demanding graphical and physics calculations of the UE5 environment necessitated a powerful machine to maintain a consistent high frame rate, which is critical for user comfort and to prevent VR sickness.

**Software:**

Figure 4: The Meta Quest 3 headset and Touch Plus controllers used in the experiment.

- *Development Engine*: The entire virtual environment and all its interaction logic were developed in UE5.
- *Plugins*: Several key plugins were integrated into the UE5 project to extend its core functionality:
  1. *Logic Driver Lite*: This plugin was used for the visual design and implementation of the FSMs. It provided a framework for creating and managing the states and transitions that manage the SRL's autonomous behavior during the assembly tasks [42].
  2. *Runtime Speech Recognizer*: To implement hands-free voice commands, this plugin was utilized. It integrates OpenAI's Whisper model to provide high-accuracy speech-to-text capabilities, which were used to trigger system events [43].
  3. *JSON Blueprint*: This utility plugin was essential for data management. It was used to structure and serialize all the collected experimental data (including task completion times, error counts, 3D path data, etc.) into a standard JSON format for easy export and analysis in external programs [44].

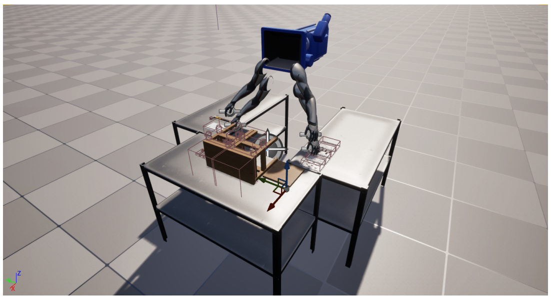
### 3.2.2 Configuration of Experimental Conditions

To systematically investigate the research questions, a within-subjects study was conducted in which each participant experienced three distinct experimental conditions. These conditions were designed to compare unassisted performance against two different modes of autonomous robotic assistance.

1. **Natural Limbs Only (Baseline Condition)**: This condition served as the experimental control to establish a performance baseline. Participants were instructed to perform the entire stool assembly task using only their two virtual hands, without any form of robotic assistance. All steps, from grabbing parts and tools to performing the final assembly, were carried out manually by the user. The data from this condition provides a benchmark for task completion time, error, workload and UX against which the assistive conditions can be measured.

2. **Autonomous SRL Collaboration**: In this condition, the user's VR Pawn was equipped with a pair of supernumerary robotic limbs that acted the same as an autonomous collaborative partner would. The user did not have direct manual control over the SRLs. Instead, the SRLs were governed by a FSM. This condition was designed to evaluate the impact of a wearable autonomous assistant on task performance and UX, addressing both RQ1 and RQ2 and for a direct embodiment evaluation addressing RQ3. The in-editor view of this setup is shown in Figure 5a

3. **Autonomous Cobot Collaboration**: This condition was designed to be functionally analogous to the SRL condition, but with a key difference in the form of the robotic assistant. Instead of wearable limbs, the user collaborated with a cobot present in the virtual workspace. This cobot was governed by the same FSM logic as the SRLs, performing the identical set of assistive sub-tasks to help the user with the assembly. The primary purpose of this condition was to directly compare the UX of collaborating with SRL versus a robotic partner, specifically to investigate differences in perceived workload and Human-Robot Interaction to address RQ2. The participant's first-person point-of-view for this condition is visualized in Figure 5b.



(a) The Autonomous SRL condition (in-editor view), showing the wearable limbs attached to the user's pawn.

(b) The Autonomous Cobot condition (participant's point-of-view), showing the external robot partner in the shared workspace.

Figure 5: Visualization of the two autonomous assistance conditions.

## 3.3 Experiment Procedure

The experiment involved three sequential phases for each participant. Following informed consent and demographics, users engaged in a short VR tutorial session in which they learned to navigate through and interact with the VR environment and controls. Participants then performed the stool assembly task under the three experimental conditions (Natural Limbs Only, Autonomous SRL, and Autonomous Cobot) in a counterbalanced order, ensuring that the performance in any given condition was not biased by the order in which it was presented. Immediately following each of the three trials, the execution was paused for the completion of post-condition questionnaires. The entire session concluded with a final post-experiment questionnaire and a debriefing to gather qualitative feedback.

### 3.3.1 Pilot Study

In preparation for the main study, a small-scale pilot study was conducted. This early phase had three primary objectives: (1) to identify and resolve any critical software bugs within the VR environment; (2) to establish an average duration for the entire experimental session to better schedule participants; (3) to validate the fairness of the proposed experimental conditions.

A key finding from the pilot study concerned the manual SRL control mode, which utilized polar coordinates. It was clear that this control scheme, as expected, was too complicated and cognitively demanding for novice users. This led to disproportionately long task times and high levels of frustration, making it an unfair comparison against the other conditions. Based on this outcome, the decision was made to remove the manual SRL control condition from the main experiment. This allowed the study to focus more directly on the research questions comparing unassisted performance with autonomous assistance (from both the SRL and the Cobot).

### 3.3.2 Participant Introduction and Instructions

The introduction of the participants was designed to ensure each individual was comfortable and well-informed before beginning the main experiment. At the beginning of the sessions participants were welcomed and given a brief explanation of the study's purpose, avoiding the introduction of any bias. They were then asked to read and sign an informed consent form and complete a brief demographics questionnaire (Table 7). After these preliminary steps, the participant was provided with the VR headset and controllers. To learn the interaction mechanics, they were introduced to a non-task-related "VR Tutorial" level. This interactive tutorial allowed them to practice basic actions such as moving, looking around, picking up and placing objects and utilizing tools within the virtual environment. This introduction phase continued until the participant demonstrated a clear understanding of the fundamental controls, ensuring they were fully prepared to proceed with the first experimental task.

### 3.3.3 Virtual Scenario Execution

Once the tutorial level was completed, the participant began the virtual scenario execution for the first of the three assigned experimental conditions. In each trial, the participant's primary objective was to fully assemble the virtual stool. To ensure they could follow the whole procedure, they were guided by the in-game instruction manual that visually presented the next steps required for the assembly. The participant's specific actions and interactions within the environment were determined by the condition assigned for that trial, whether they were working unassisted, with the help of the autonomous SRL or in collaboration with the external cobot. Throughout the entire duration of the task, the system automatically logged a comprehensive set of objective performance metrics in the background, including task completion timestamps, the number of dropped objects, 3D hand-tracking path data and head turn angles. Upon successful completion of the stool, the trial terminated, and the system finalized the data log for that specific condition.

### 3.3.4 Post-Experiment Data Collection

Immediately following the completion of the assembly task in each of the three conditions, the data collection shifted from objective performance metrics to subjective user feedback. Participants removed the VR headset and were directed to a computer to fill out a set of digital questionnaires. This process was repeated after each trial to guarantee feedback was captured while the experience was still fresh. To gather a comprehensive dataset, a mix of core and condition-specific questionnaires was used. After every condition, participants gave feedback in regards of the perceived workload and the UX to assess usability and general experience. To facilitate a direct comparison of the collaborative experience for RQ2, a questionnaire about collaborative task experience was administered after both the Autonomous SRL and the Autonomous Cobot conditions. To specifically address RQ3, a standard questionnaire for virtual embodiment was completed by participants only after the Autonomous SRL condition to measure their sense of embodiment with the wearable system. Finally, a post-experiment questionnaire was also administered to obtain information regarding condition preference.

## 3.4 Data Acquisition

Data acquisition for this study was done in two ways, capturing both objective performance metrics and subjective user feedback. Objective data was automatically logged by the UE5 application, while subjective data was collected through a series of digital questionnaires administered after each condition.

### 3.4.1 Objective Metrics

To provide a quantitative evaluation of task performance and efficiency, a set of objective metrics was logged by the system during each experimental trial. These metrics were chosen to capture not only the final outcome of the task, but also the quality and efficiency of the user's movements and interactions.

- Task Completion Time: The total time elapsed from the beginning to the successful completion of the stool assembly was the primary measure of overall performance. Besides the whole task duration, timestamps for some particularly important assembly steps were recorded, enabling a detailed investigation of the phases of the task.
- Error Count: Task proficiency was also assessed by tracking errors, which were quantified as the total count of dropped objects, including both assembly parts and tools. A larger number of drops may reflect more task difficulty or decreased dexterity in a particular condition.
- Path and Kinematic Data: The 3D coordinates of the user's hands and the robotic limbs (in the assistive conditions) were continuously registered throughout each trial. This rich path data was collected for post-hoc analysis of movement efficiency, allowing for the calculation of metrics such as total path length, workspace volume and other kinematic properties like average speed and jerk.
- Efficiency Metrics: To further assess efficiency, the system logged the total number of grab actions performed by each hand. These metrics can provide insights into cognitive load, hesitation or the user's confidence and fluency in manipulation.
- Head Orientation: The user's head orientation was tracked over time to serve as a substitute for their attentional focus. This data enables analysis of where the user is looking at any given moment, which can reveal patterns in how they divide their attention between the assembly task, the instruction manual and the actions of the robotic collaborator.

### 3.4.2 Subjective Metrics

To complement the objective performance data, subjective metrics were collected using a series of validated questionnaires administered after the relevant experimental conditions. These instruments were selected to quantify the user's personal experience regarding workload, usability and their perception of the robotic systems.

- Workload (NASA-TLX): The participant's perceived workload was recorded using the NASA Task Load Index (NASA-TLX) after every condition to measure the participant's perceived workload [41]. This provided a quantitative measure of the mental, physical and temporal effort needed to perform the assembly task, allowing for a direct comparison of the cognitive and physical demands. (Table 8)

- User Experience (UEQ-S): The short form of the User Experience Questionnaire (UEQ-S) was used to assess the overall, pragmatic and hedonic qualities of the interaction in each condition [23]. This captured user perceptions on aspects such as efficiency, clarity and excitement. (Table 9)

- Human-Robot Collaboration (Collaborative Task Experience Questionnaire): In order to compare the collaboration experience between both the Autonomous SRL and the Autonomous Cobot conditions, a multi-part questionnaire was administered at the conclusion of both task sessions.. This custom instrument combined several measures: (i) a set of Likert-scale questions adapted from HRI literature to assess Collaboration Quality and the user's Sense of Co-Presence with the partner [37, 40] (Table 11), and (ii) the full Godspeed Questionnaire to gather data on key user perceptions of the robotic partner's attributes [39]. (Table 11)

- Embodiment (VEQ): To specifically address RQ3, the standard Virtual Embodiment Questionnaire (VEQ) (adapted with slightly different wordings to match the use case) was administered only after the Autonomous SRL condition [25]. This questionnaire was used to quantify the participants' sense of body ownership, agency and change in perceived body schema with respect to the wearable autonomous limbs. (Table 10)

- Overall Preference: At the end of the entire session, the participants were asked to provide a final preference ranking of the three conditions [38]. This provided a final rating of user satisfaction with each interaction mode. (Table 12)

### 3.4.3 Data Logging Format

All objective metrics generated during each experimental trial were automatically structured and saved into a single data file to ensure data integrity and facilitate subsequent analysis. The chosen format for this data was JSON (JavaScript Object Notation). This format was selected for its ideal balance of human-readability, which is useful for debugging and machine-parsability, which allows for easy importation into data analysis scripts and software.

For each completed trial, a unique JSON file was created. The file consists of a single parent object containing a series of key-value pairs that correspond to the objective metrics. This includes simple numerical values such as the total number of dropped objects (n_Drops) and cumulative grabs (SRL_R_N_Grab). More complex data, like the 3D path data, was stored as a nested object containing parallel arrays for timestamps and the corresponding (x, y, z) spatial coordinates. Finally, boolean flags were included in each file to identify the experimental condition (solo, cobot, SRL) under which the data was recorded. This structured and comprehensive logging format ensures that all performance data is captured accurately and is readily available for detailed post-hoc analysis (a JSON file sample can be checked in the Appendix, A.4).

## 3.5 Data Processing

Following the completion of all the experiments, a data processing pipeline characterized by custom Python scripts was used to transform the raw data logs into a structured format suitable for statistical analysis. This involved a two-stage process. The first stage consisted of preprocessing steps to aggregate the individual data files and calculate primary outcome metrics. The second, more intensive stage focused on the preparation and analysis of the 3D path data to derive key kinematic metrics related to movement efficiency and smoothness. The goal of this pipeline was to prepare a clean and comprehensive dataset to formally test the research hypotheses.

### 3.5.1 Preprocessing Steps for Quantitative Data

The initial preprocessing began with a script that programmatically renamed the raw, data files exported from Unreal Engine. This script reads the boolean flags (solo, cobot) inside each JSON file to determine the experimental condition and inserts it at the beginning of the filename, providing clear identification for each trial (participantID-condition-randomString.json).

Subsequently, all individual JSON files were loaded and aggregated into a single master pandas DataFrame. Primary measurements were derived or calculated from this body. Simple numerical values such as the number of dropped objects (n_Drops) and the grab counts for each hand were extracted directly. Metrics such as total_hand_grabs were computed by summing the grab counts of the user's left and right hands. The array of timeStamps was processed to calculate the overall total_time for the task, as well as the duration of each individual assembly stage by calculating the difference between consecutive timestamps.

### 3.5.2 Preparation for Path Data Analysis

A separate pipeline was implemented to analyze the 3D path data and derive objective metrics for movement quality. The time-stamped (x, y, z) coordinate arrays for each of the user's hands were extracted from the dataset for each trial. To ensure the integrity of the kinematic calculations, a filtering step was first applied to detect and remove anomalous jumps at the start of a path, which could happen from system resets or tracking initialization.

Following this cleaning step, the script performed numerical differentiation on the positional data with respect to time to compute the path's kinematic properties. This process generated the instantaneous velocity (first derivative), acceleration (second derivative) and jerk (third derivative) of the movement. From these, final summary metrics were calculated for each path, including the total path length, the average movement speed, and the average jerk, which serves as a quantitative measure of movement smoothness. Also, the workspace volume for each hand and for both hands combined was computed using a Convex Hull algorithm. This method computes the smallest possible convex shape that encloses all the path points, providing a quantitative measure of the total volume of the user's interaction space. An example of this calculation is visualized in Figure 6. These derived metrics provide an objective view of user efficiency and motor control across the conditions.

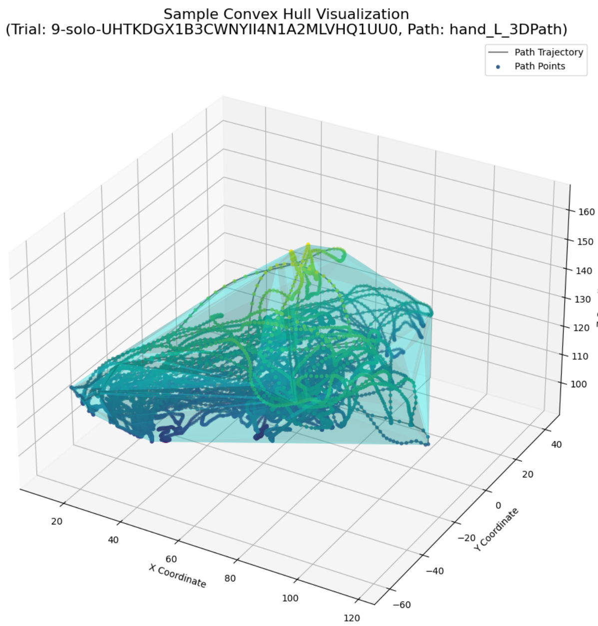



Figure 6: An example visualization of the Convex Hull calculation for a single hand path from a random trial. The points of the path are enclosed by the semi-transparent volume.

## 3.6 Analysis Methodology

All quantitative and questionnaire data were processed and analyzed using custom scripts written in Python, leveraging the pandas library for data management and the scipy.stats and statsmodels libraries for statistical testing. A significance level (alpha) of $\alpha = 0.05$ was used for all statistical tests to determine significance.

To compare the three experimental conditions (Solo, SRL, Cobot) for the objective performance metrics and the multi-condition questionnaires (NASA-TLX, UEQ-S), a one-way repeated measures ANOVA was the primary statistical test employed. This test was used to determine if there was a significant effect of the condition on each metric. If the ANOVA produced a significant result ($p < .05$), post-hoc paired t-tests were conducted for each pairwise comparison (Solo vs. SRL, SRL vs. Cobot, and Cobot vs. Solo). To control the family-wise error rate across these multiple comparisons, the resulting p-values were adjusted using the Holm–Bonferroni correction. A corrected p-value of less than 0.05 was considered statistically significant.

For the direct comparison between the two collaborative conditions (SRL vs. Cobot) on the Collaboration and Godspeed questionnaire data, independent samples t-tests were used to determine if there were significant differences in user ratings between the two systems.

A distinct non-parametric method was used to analyze the distribution of head turning angles. All head turn angle data points from each trial within a condition were pooled together. A Kernel Density Estimation (KDE) was then applied to each condition's pooled data to generate a smooth probability distribution. The peak height of this KDE, which reflects the concentration of head movements around the most frequent angle, was used as the primary metric for comparison. To enable a robust statistical test, a bootstrapping procedure (n=2000 iterations) was employed. In each iteration, the data was resampled with replacement, and the peak height of the resulting KDE was recorded, generating a distribution of peak heights for each condition. A statistically significant difference between two conditions was determined if the 95% confidence interval of the difference between their bootstrapped peak height distributions did not include zero. An additional check for practical significance was performed to ensure that any statistically significant difference was also meaningful in magnitude.

Finally, to address the research question regarding embodiment (RQ3), the VEQ scores from the SRL condition were analyzed using a one-sample t-test for each sub-scale (Ownership, Agency and Change in Body Schema). This test was used to determine if the mean reported scores were statistically significantly different from the neutral midpoint of 4 on the 7-point Likert scale.

# Chapter 4

# Results

This chapter presents the quantitative and qualitative results obtained from the experimental study. The findings are structured in a way that directly responds to the research questions outlined in Chapter 1. The chapter begins with an overview of the participant demographics, followed by a detailed analysis of the objective performance metrics, including task completion time, error rates and movement efficiency. The subjective data from the NASA-TLX, UEQ-S, VEQ and the custom collaboration questionnaires are then presented to evaluate workload, UX and embodiment. Last, a summary of the key statistics is provided to introduce the discussion in the next chapter.

## 4.1 Participant Demographics

A total of 24 participants (18 male, 6 female) successfully completed the experiment. The age of the participants ranged from 21 to 28 (mean age = 24.5 years, SD = 1.64). The majority of the participants were right-handed (22), with two participants being left-handed.

Regarding prior technical experience, most participants reported they play video games often, and a majority played at least once or twice a month. Experience with virtual reality was more varied; while many had some minimal experience, a significant number had never used VR before. Experience with controlling physical or virtual robots was the least common among the participants, though a notable portion reported having weekly or more frequent interaction with robotic systems. A full breakdown is presented in Figure 7.


Figure 7: Summary of participant demographics, showing the gender distribution (left) and the self-reported frequency of experience with relevant technologies (right).

## 4.2 The Effect of Robotic Assistance on Task Performance, Workload and User Experience (Addressing RQ1)

To evaluate the impact of robotic assistance on user performance, workload and UX the three experimental conditions were compared across several objective and subjective metrics. A one-way repeated measures ANOVA was conducted for each metric, followed by post-hoc comparisons using Paired t-tests with Holm–Bonferroni Correction where significant main effects were found.

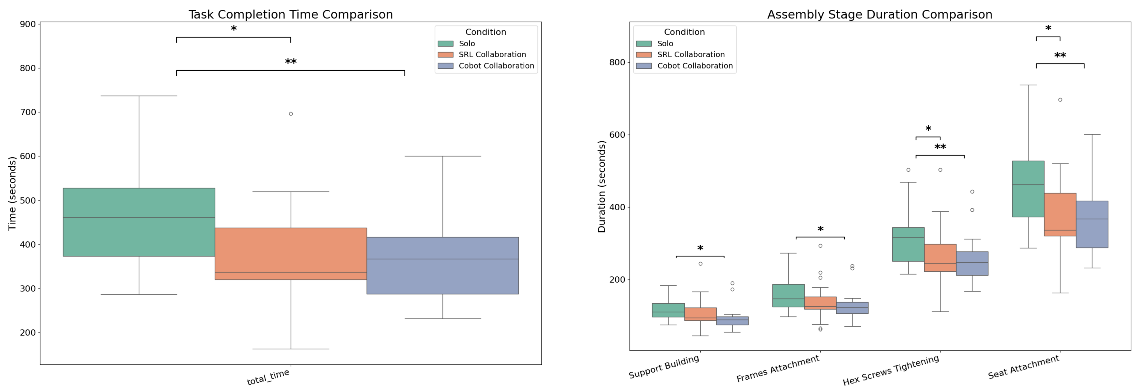
### 4.2.1 Task Completion Time and Errors

Task performance was mainly measured by the total time taken to complete the assembly and the number of errors made. A one-way repeated measures ANOVA revealed a statistically significant main effect of condition on task completion time ($F(2, 46) = 7.34$, $p = 0.0017$). Post-hoc comparisons using Paired t-tests with Holm–Bonferroni correction revealed that participants were significantly faster in both the SRL Collaboration ($p = 0.0030$) and Cobot Collaboration ($p = 0.0143$)

conditions compared to the Solo condition. There was no significant difference in completion time between the SRL and Cobot conditions (p = 0.7693) (Table 2). This means that both types of robotic assistance contributed to a significant reduction in task completion time as depicted in Figure 8.

Table 2: Post-Hoc Pairwise Comparisons for Task Completion Time using Paired t-tests with Holm–Bonferroni Correction

| **Group 1** | **Group 2** | **Mean Diff.** | **t-statistic** | **p-value** | **Significant** |
|---|---|---|---|---|---|
| Cobot | Solo | -104.80 | -3.764 | 0.0030 | **Yes** |
| SRL | Solo | -114.26 | -2.952 | 0.0143 | **Yes** |
| Cobot | SRL | 9.46 | 0.297 | 0.7693 | No |




(a) Overall Task Completion Time

(b) Duration of Individual Assembly Stages

Figure 8: Comparison of task and stage completion times across the three conditions. Error bars represent standard deviation. Asterisks denote the level of statistical significance: p < 0.1 (*), p < 0.05 (**), p < 0.01 (***), p < 0.001 (****).

With respect to the number of dropped items (error rate), the ANOVA revealed that there were no significant differences between the three conditions (F(2,46) = 2.45, p = 0.0971).

### 4.2.2 Motion Economy and Efficiency

The users' motion efficiency was quantified by the number of manual grabs, the movement distance and volume of their hands.

For total hand grabs, there was a significant main effect of condition (F(2, 46) = 11.0805, p = 0.0001). The post-hoc analysis showed that participants in the assistive conditions performed significantly fewer grabs than in the Solo condition: Cobot (p = 0.0016) and SRL (p = 0.0438).

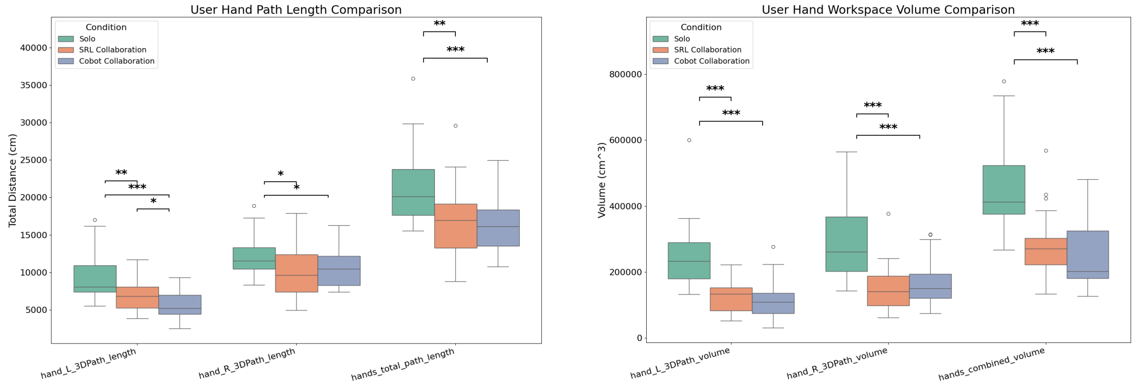
A very significant effect of condition was found for the total path length of the user's hands (F(2, 46) = 12.75, p < 0.0001) and the combined workspace volume (F(2, 46) = 25.16, $p < 0.0001$) (Figure 9). Post-hoc tests confirmed that both the SRL and Cobot conditions resulted in significantly shorter path lengths (Table 3) and smaller workspace volumes (Table 4) compared to the Solo condition (all $p < 0.05$). This provides strong evidence that both assistive systems significantly reduced the amount of work required from the user.

Table 3: Post-Hoc Pairwise Comparisons for Total Hand Path Length using Paired t-tests with Holm–Bonferroni Correction

| **Group 1** | **Group 2** | **Mean Diff.** | **t-statistic** | **p-value** | **Significant** |
|---|---|---|---|---|---|
| Cobot | Solo | -5045.520 | -5.124 | 0.0001 | **Yes** |
| SRL | Solo | -4457.700 | -3.376 | 0.0052 | **Yes** |
| Cobot | SRL | -587.820 | -0.631 | 0.5344 | No |

Table 4: Post-Hoc Pairwise Comparisons for Combined Hand Workspace Volume using Paired t-tests with Holm–Bonferroni Correction

| **Group 1** | **Group 2** | **Mean Diff.** | **t-statistic** | **p-value** | **Significant** |
|---|---|---|---|---|---|
| Cobot | Solo | -202671.392 | -6.817 | $< 0.0001$ | **Yes** |
| SRL | Solo | -178923.306 | -5.101 | 0.0001 | **Yes** |
| Cobot | SRL | -23748.086 | -0.833 | 0.4135 | No |




(a) Total Hand Path Length

(b) Combined Hand Workspace Volume

Figure 9: Comparison of user motion economy across the three conditions. Figure (a) shows the total distance traveled by the user's hands. Figure (b) shows the total volume of the workspace occupied by the user's hands. Asterisks denote the level of statistical significance: $p < 0.1$ (*), $p < 0.05$ (**), $p < 0.01$ (***), $p < 0.001$ (****).

### 4.2.3 Movement Quality

Movement quality was assessed using the average speed and jerk of the user's hands. Higher jerk would indicate less smooth and more corrective movements.

The analysis showed a significant effect of condition on the average speed of the user's hands ($F(2, 46) = 8.47$, $p = 0.0007$). Post-hoc tests revealed that participants moved their hands significantly faster in the SRL Collaboration condition ($p = 0.0023$) when compared to the Solo condition. While the difference between the Cobot Collaboration and Solo conditions did not reach the threshold for significance ($p = 0.0978$), the data indicates a strong trend towards faster movements with cobot assistance as well (Table 5 and Figure 10a). This suggests that the assistance provided by the robotic partners allowed users to perform their manual actions with greater speed and confidence.

The analysis of movement smoothness, measured by average jerk, gave a surprising result. While the ANOVA confirmed a significant effect of the experimental condition ($F(2, 46) = 7.21$, $p = 0.0019$), post-hoc tests revealed that movements in the Solo condition were actually smoother (exhibiting significantly lower average jerk) than in both the SRL ($p = 0.0183$) and Cobot ($p = 0.0439$) conditions (Table 6). This counterintuitive finding suggests a fundamental shift in the nature of the

Table 5: Post-Hoc Pairwise Comparisons for Average Hand Speed using Paired t-tests with Holm–Bonferroni Correction

| **Group 1** | **Group 2** | **Mean Diff.** | **t-statistic** | **p-value** | **Significant** |
|---|---|---|---|---|---|
| Cobot | Solo | 2.333 | 2.884 | 0.0168 | **Yes** |
| SRL | Solo | 3.904 | 4.007 | 0.0017 | **Yes** |
| Cobot | SRL | -1.571 | -1.478 | 0.1530 | No |

user's actions when collaborating with a robot. The large and fluid reaching motions required to find and collect parts in the Solo condition appear to be smoother than the series of short, abrupt and precise hand-off or placement motions that characterize interaction with an assistant. In essence, while robotic assistance simplified the overall task, it transformed the user's role into one requiring more frequent, less continuous movements, leading to a quantifiable increase in jerk (visible in Figure 10b).

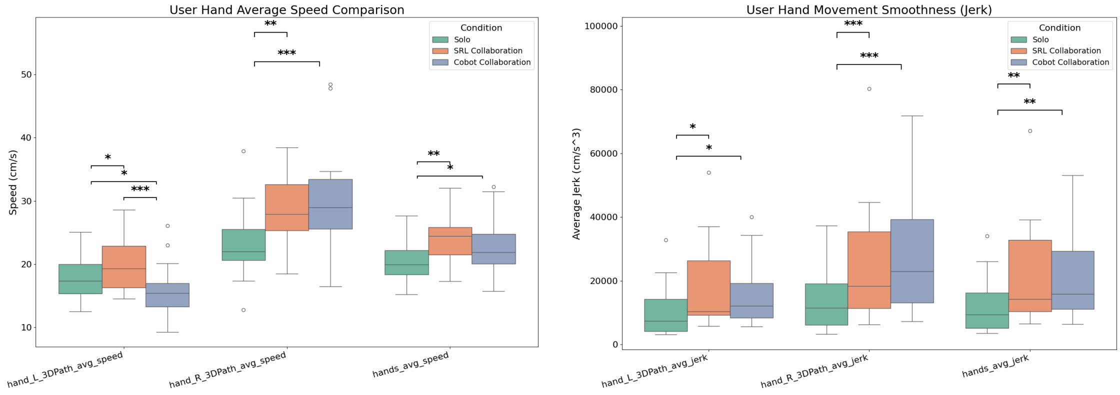
Table 6: Post-Hoc Pairwise Comparisons for Average Hand Movement Jerk using Paired t-tests with Holm–Bonferroni Correction

| **Group 1** | **Group 2** | **Mean Diff.** | **t-statistic** | **p-value** | **Significant** |
|---|---|---|---|---|---|
| Cobot | Solo | 9876.130 | 3.797 | 0.0023 | **Yes** |
| SRL | Solo | 8663.889 | 3.882 | 0.0023 | **Yes** |
| Cobot | SRL | 1212.241 | 0.344 | 0.7338 | No |

### 4.2.4 Attentional Focus

To analyze the user's attentional focus across conditions, head orientation data was continuously tracked. The comparative distribution of head turn angles is visualized in Figure 11 using a Kernel Density Estimate (KDE) plot. This method provides a smooth curve where the y-axis ('Density') represents the estimated probability of observing a particular head turn angle, revealing distinct patterns for each condition.

The Solo condition exhibits the broadest distribution, indicating substantial den-




(a) Average Hand Speed (b) Average Hand Jerk (Smoothness)

Figure 10: Comparison of user hand movement quality across the three conditions. Figure (a) shows the average speed of the hands, where higher is faster. Figure (b) shows the average jerk, where lower indicates smoother movements. Error bars represent standard deviation. Asterisks denote the level of statistical significance: $p < 0.1$ (*), $p < 0.05$ (**), $p < 0.01$ (***), $p < 0.001$ (****).

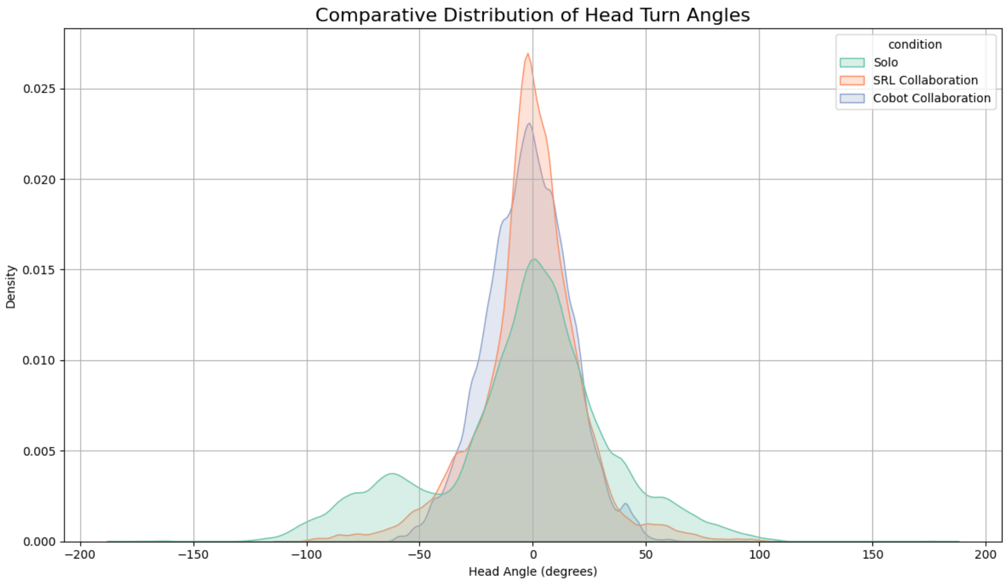



Figure 11: A Kernel Density Estimate (KDE) plot showing the distribution of head turn angles for each experimental condition. The y-axis represents the probability density, with higher peaks indicating more frequently held head positions.

sity over a wide range of angles, which is consistent with participants in isolation turning their gaze away from the central task area to scan for parts and tools. This visual observation is confirmed by the statistical analysis; the peak height of the Solo condition's KDE (Peak = 0.0143) was found to be statistically significantly lower than both assistive conditions, indicating less focused attention.

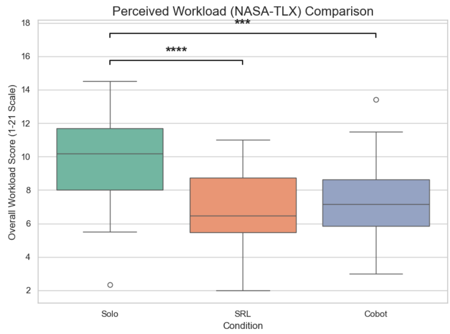
In comparison, both the SRL and Cobot Collaboration conditions show much narrower distributions, with peaks at 0 degrees (forward-facing). This indicates that when receiving assistance, participants could maintain a more sustained focus on the primary assembly task. Bootstrap comparison of the distributions statistically validated this, revealing that the peak of KDE for both the SRL (Peak = 0.0227, 95% CI [0.0214, 0.0240]) and Cobot (Peak = 0.0229, 95% CI [0.0215, 0.0244]) conditions were significantly higher than the Solo condition. While a subtle visual difference exists between the two assistive modes in the plot, the statistical test found no significant difference between the peak heights of the SRL and Cobot conditions ($\Delta$ = 0.0002, 95% CI [-0.0018, 0.0022]). This suggests that both assistive systems were equally effective at reducing the need for users to turn their heads away from the main task. Overall, the head orientation data provides an objective and statistically significant measure supporting the finding of reduced attention switching in the assistive conditions.

### 4.2.5 Perceived Workload

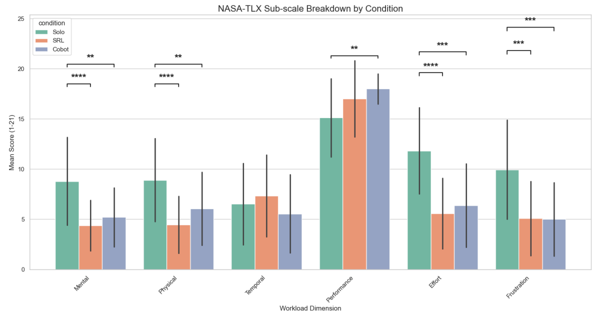
To assess the subjective workload, the NASA-TLX was administered after each condition. A one-way repeated measures ANOVA on the overall workload score (Raw TLX) revealed a highly significant main effect of condition ($F(2, 69) = 12.921$, $p < 0.0001$).

Post-hoc tests confirmed that this effect was due to the high workload of the Solo condition, which was rated as significantly more demanding than both the SRL Collaboration ($p = 0.0001$) and Cobot Collaboration ($p = 0.0004$) conditions (visible in Figure 12a). Important to note, there was no statistically significant difference in the overall perceived workload between the SRL and the Cobot ($p = 0.8613$).

Such an interpretation is further supported by the analysis of the individual sub-scales (Figure 12b). Significant differences were found for Mental Demand, Physical Demand, Effort, and Frustration, with post-hoc tests consistently showing that both robotic assistants significantly reduced these aspects of workload compared




(a) Overall Workload Score (Raw TLX)




(b) Workload Sub-scale Breakdown

Figure 12: Comparison of perceived workload (NASA-TLX) across the three conditions. Figure (a) shows the distribution of the condensed overall workload scores. Figure (b) shows the mean scores for each of the six individual sub-scales. Asterisks denote the level of statistical significance: $p < 0.1$ (*), $p < 0.05$ (**), $p < 0.01$ (***), $p < 0.001$ (****).

to working alone (Table 14). This indicates that both systems were equally effective at reducing the perceived burden of the task.

## 4.3 User Experience of Collaboration: SRL vs. Cobot (Addressing RQ2)

While the objective performance metrics indicated that both the SRL and Cobot systems provided a similar level of assistance, a key goal of this research was to understand the differences, if any, in the subjective UX between these two distinct paradigms (wearable vs. external). This section presents the results from the questionnaires designed to compare the two collaborative conditions.

### 4.3.1 User Experience

Both the task-related (Pragmatic Quality) and the non-task-related (Hedonic Quality) components of the interaction were evaluated with the UEQ-S. A one-way ANOVA revealed a highly significant main effect of condition on all eight items of the questionnaire (all $p < 0.0001$) (in Appendix A, Table 13).

Post-hoc t-tests confirmed that both the SRL and Cobot conditions were rated significantly higher than the Solo condition on all scales (in Appendix A, Table 15). When comparing the two robotic systems, no significant difference was found in terms of pragmatic quality (usability) ($p = 0.9514$). An important distinction, however, emerged in the hedonic quality. The overall Hedonic Quality score for the SRL was statistically significantly higher than for the Cobot ($p = 0.0070$). This is further supported by the analysis of the individual items, where the SRL was rated as significantly more "Inventive" ($p = 0.0017$) and "Leading Edge" ($p = 0.0059$). than the Cobot. Taken together, these results suggest that the wearable system provided a more novel and engaging experience for the participants and it is possible that a larger sample size would have resulted in a significant difference for the overall hedonic score as well (Figure 13).

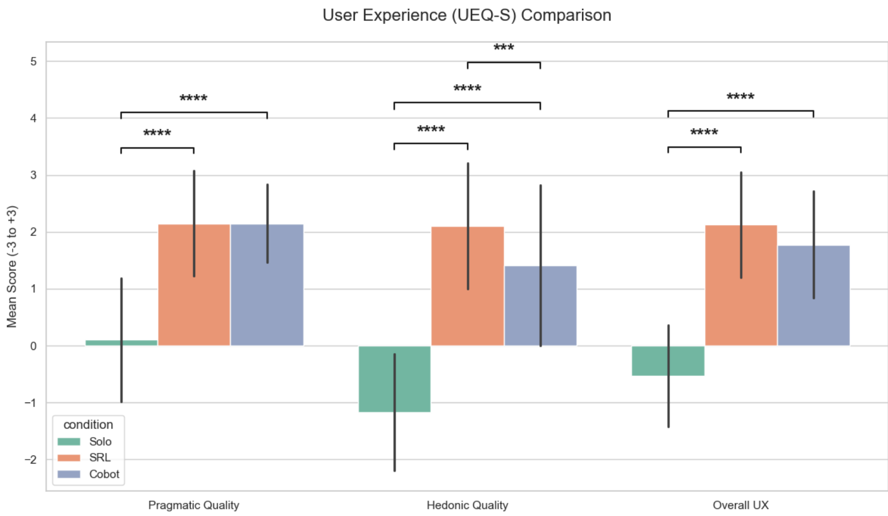



Figure 13: Comparison of the condensed UEQ-S scores for Pragmatic Quality, Hedonic Quality, and the Overall User Experience across the three conditions. Error bars represent standard deviation. Asterisks denote the level of statistical significance: $p < 0.1$ (*), $p < 0.05$ (**), $p < 0.01$ (***), $p < 0.001$ (****).

### 4.3.2 Collaboration and Co-Presence

To evaluate the quality of the partnership, participants rated their interaction with each robotic assistant. Although the first t-tests on the 7-point scale questions showed no statistically significant difference between the SRL and Cobot (also visible from the plot in Figure 14), the forced-choice preference questions asked at the end of the experiment show a different picture.

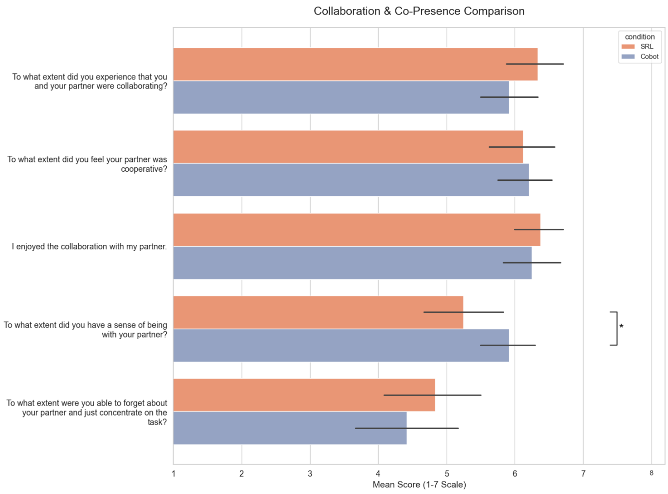



Figure 14: Comparison of user ratings for the custom collaboration and co-presence questions between the SRL and Cobot conditions. Error bars represent standard deviation. Asterisks denote the level of statistical significance: $p < 0.1$ (*), $p < 0.05$ (**), $p < 0.01$ (***), $p < 0.001$ (****).

When asked which partner gave them a stronger sense of "being with you", a majority of participants (58.3%) chose the SRL, compared to 25.0% for the Cobot (in appendix A, Figure 19). Similarly, when asked with which partner they felt they were "doing something together" the most, 58.3% of participants selected the SRL, compared to 33.3% for the Cobot (in Appendix A, Figure 18). A correlation analysis further revealed a strong positive relationship between these two perceptions, as shown in the heatmap in Figure 15. Together, these findings indicate that, while rated equally in terms of general collaboration, the wearable's physically worn approach lent to a greater subjective feeling of presence and teamwork.

### 4.3.3 Perceived Partner Attributes (Godspeed)

The Godspeed Questionnaire was used to evaluate how users perceived the intrinsic characteristics of each robotic partner. Independent samples t-tests on the condensed sub-scales revealed significant differences in how "human-like" and "alive" the partners were perceived to be.

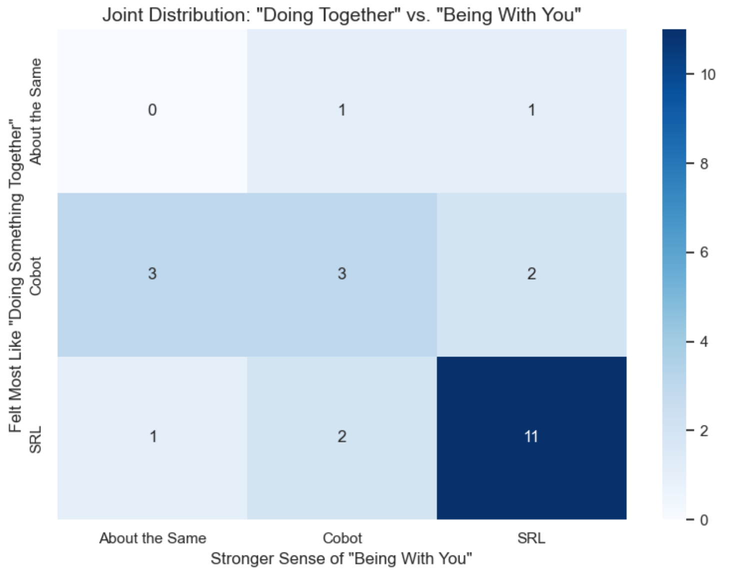



Figure 15: A heatmap showing the correlation between participants' final preference ratings for feeling like they were "doing something together" with the partner and their feeling of "being with" the partner. The strong positive correlation suggests these two subjective feelings are closely related.

A statistically significant difference was found for the Anthropomorphism scale ($p = 0.0153$) and the Animacy scale ($p = 0.0001$), with the SRL being rated significantly higher on both dimensions. An analysis of the individual items reveals that this was driven by the SRL being perceived as more Lifelike ($p = 0.0041$), Human-like ($p = 0.0187$), Lively ($p = 0.0125$), Organic ($p = 0.0012$), Interactive ($p = 0.0001$) and Responsive ($p = 0.0002$).

The same trend emerged for the overall Perceived Intelligence scale, which reached statistical significance ($p = 0.0123$), indicating the SRL being perceived as more intelligent. This was supported by a significant difference on the items of Knowledge ($p = 0.0051$), Competence ($p = 0.0183$) and Intelligence ($p = 0.0448$) where the SRL was rated higher. No significant differences were found for the overall Likeability or Perceived Safety scales, suggesting users felt equally comfortable and positive towards both systems in these respects.

Together, these results indicate that while both partners were considered equally likable and safe, the wearable form factor of the SRL contributed to a perception of it being a more animate, human-like and intelligent agent than the external Cobot (see Table 16 in Appendix A for full details).

### 4.3.4 Overall Preference

The final preference question provided a clear result. In response to the question of which robotic partner participants preferred collaborating with overall, a significant majority of participants (62.5%) chose the SRL. On the other hand, 29.2% preferred the Cobot, and only 8.3% rated the experience as about the same. This aligns with the findings from the UEQ-S and Godspeed questionnaires, providing final support for the hypothesis that the wearable SRL offers a superior UX.

## 4.4 Embodiment of an Autonomous Partner (Addressing RQ3)

To address the third research question, about how much users might feel embodied over an autonomous robotic partner, the VEQ was administered after the SRL condition. The mean score for each of the three sub-scales (Ownership, Agency and Change in Body Schema) was compared against the neutral midpoint of the 7-point Likert scale (a score of 4) using one-sample t-tests.

The analysis revealed a nuanced but clear sense of embodiment. The mean score for Ownership ($M = 4.86$, $SD = 1.44$) was found to be statistically significantly higher than the neutral value of 4 ($t(24) = 2.91$, $p = 0.0078$). This indicates that participants, on average, agreed with statements that the robotic arms felt like their own.

Perhaps the most surprising finding was the highly significant result for the Agency sub-scale ($M = 5.03$, $SD = 1.18$). The mean score was significantly higher than the neutral midpoint ($t(24) = 4.29$, $p = 0.0003$). This is a counterintuitive result; it suggests that even without any direct manual control, participants felt a strong sense of control and intention over the autonomous partner's actions. This feeling of agency likely comes from the robot's predictable and task-relevant behavior, which was perceived as being in sync with the user's own goals.

Contrary to the initial hypothesis, the score for the Change in Body Schema subscale (M = 3.03, SD = 1.14) was statistically significantly lower than the neutral midpoint (t(24) = -4.15, p = 0.0004). This indicates that participants actively disagreed with statements that suggested their own physical body felt different in shape, size or weight, rejecting this aspect of embodiment.

In summary, these results provide strong but nuanced support for H3. While the hypothesis that users would feel embodied was confirmed, the components driving this feeling were unexpected. The strong sense of agency, even in an autonomous system, was a more powerful factor than the anticipated change in body schema. Participants reported a significant sense of both ownership and agency over the supernumerary limbs, while simultaneously rejecting any feeling of physical alteration. These findings are visualized in Figure 16.

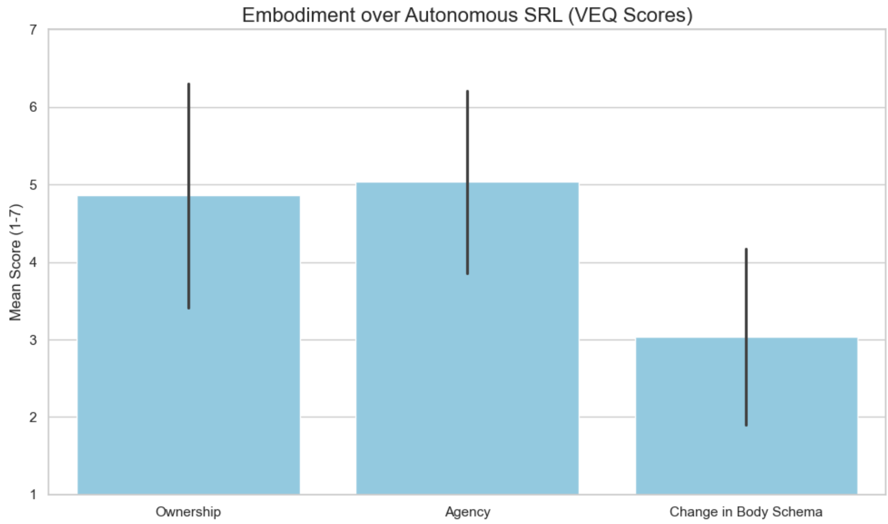



Figure 16: Mean scores for the three sub-scales of the Virtual Embodiment Questionnaire (VEQ) for the SRL condition. Error bars represent standard deviation. The dotted line at 4 indicates the neutral midpoint of the scale.

## 4.5 Summary of Key Findings

Several results came out from the statistical analysis of both the objective and the subjective data. A one-way repeated measures ANOVA revealed a significant main effect of the experimental condition on task completion time, motion economy and movement quality. Post-hoc tests confirmed that both the SRL and Cobot assistance conditions resulted in significantly faster task completion times, shorter total hand path lengths, smaller workspace volumes, greater motion confidence, but with more abrupt movements (higher average jerk) compared to the unassisted Solo condition. For these objective metrics, no significant performance difference was found between the SRL and Cobot conditions.

The analysis of the subjective questionnaire data also revealed significant differences. A series of ANOVAs on the NASA-TLX data showed that both robotic assistance conditions significantly reduced the perceived mental demand, physical demand, effort and frustration compared to the Solo condition. Similarly, the UEQ-S results indicated that both the SRL and Cobot were perceived as significantly more usable and enjoyable than working alone.

Direct comparison of the two robotic partners showed that while they were rated similarly on workload and usability, the SRL was perceived as significantly more inventive, lifelike, animate, and knowledgeable than the Cobot. Finally, a one-sample t-test on the VEQ data for the SRL condition confirmed that participants reported a sense of Ownership and, unexpectedly, Agency that was statistically significantly higher than the neutral midpoint, while the score for Change in Body Schema was significantly lower.

# Chapter 5

# Discussion

This chapter gives a more detailed analysis of the experimental results in Chapter 4. The findings are discussed in relation to the original research questions and hypotheses, and are related to the literature. The chapter begins by discussing the implications of the results for each research question and then validates the hypotheses. It then analyzes the broader meaning of the findings more generally for SRL design and HRI. Additionally, it acknowledges the limitations of the current study and concludes by providing recommendations for future research directions.

## 5.1 Robotic Assistance Improves Performance and Reduces Workload

The results offer a clear answer to the first research question: the introduction of an autonomous robotic partner significantly improves both objective performance and subjective experience compared to unassisted manual work. The significantly lower task-completion time was due mainly to the parallelization of sub-tasks; by having the robot manage part and tool handling, the user's cognitive and physical capabilities could be dedicated to focus on the main assembly process. This was confirmed by the user manual motor activity being substantially decreased as measured in shorter hand path lengths and reduced workspace volumes.

In addition, the objective results were supported by workload data from the NASA-TLX. Mental demand, physical demand, effort and frustration were significantly reported to be less when halp was given. This suggests that robotic assistance did not merely speed the task, but made it seem much easier and less stressful.

## 5.2 The Subjective Superiority of a Wearable Partner

A key point set by this study was that, even though the SRL and Cobot were equally effective for performance and workload, the subjective experiences of working with the two partners were qualitatively distinct. This distinction consistently favored the wearable SRL, leading to a clear user preference.

This preference did not originate from the functional aspects of the collaboration (participants rated both partners as equally cooperative), but rather from the perception of the robot itself. The SRL was perceived as more Lifelike, Lively, Organic, Interactive and Responsive. This group of "Animacy" ratings shows that the physical attachment and closeness of the SRLs created a stronger sense of a dynamic and "living" partner compared to the external Cobot. This was further supported by the UEQ-S, where the SRL scored significantly higher on overall Hedonic Quality than the Cobot, suggesting the experience was more engaging and enjoyable. This was driven by the SRL being perceived as significantly more “Inventive” and “Leading Edge”.

## 5.3 Embodiment of an Autonomous Agent

The findings related to the third research question provide a nuanced but powerful insight about embodiment. Results confirmed that users can experience a strong sense of Ownership and, surprisingly, Agency on a robotic partner that they do not directly control. The relatively high sense of agency may be due to the robot’s predictable, task-relevant behavior, which was perceived as synchronizing with the user’s own intentions.

in contrast to the prediction, this feeling did not transfer to a perceived change in the user's body. Participants actively disagreed with statements implying that their own body felt different, indicating that the embodiment of an autonomous partner may be a distinct phenomenon, focused more on a sense of partnership and shared intention rather than a physical modification of one's body schema.

## 5.4 The Role of Embodiment in User Preference

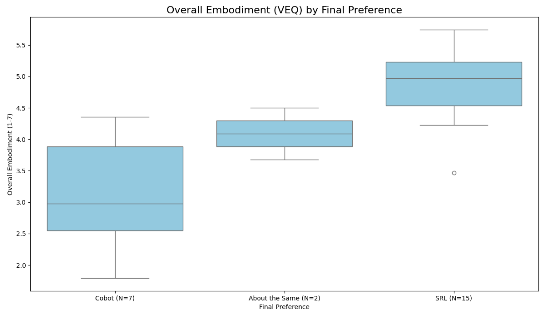
While the results for RQ2 showed a nuanced user preference for the SRL, a subsequent analysis was conducted to better understand the deeper underlying factors driving this choice. This analysis explored the relationship between the participants' final preference (SRL, Cobot, About the same) and the embodiment scores reported for the SRL condition. The findings revealed that the sense of embodiment is a key predictor of user preference.

A Kruskal-Wallis test showed a statistically significant difference in the Overall Embodiment scores among the three preferences ($H = 12.99$, $p = 0.0015$). A post-hoc Mann-Whitney U test confirmed that participants who stated a preference for SRL had a significantly higher Overall Embodiment score than those who preferred the cobot ($p = 0.0001$).

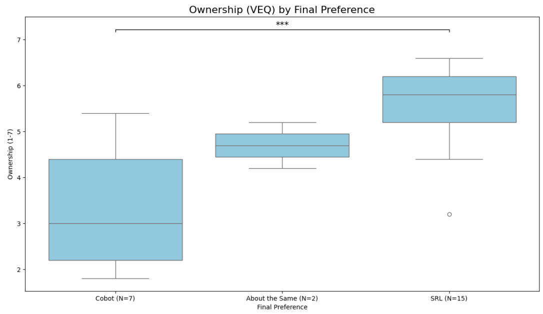
This pattern was consistent across the sub-scales of embodiment. A significant difference was found for both Ownership ($H = 11.24$, $p = 0.0036$) and Agency ($H = 9.08$, $p = 0.0107$). Post-hoc test again revealed that participants who preferred the SRL reported significantly higher scores for both Ownership ($p = 0.0017$) and Agency ($p = 0.0041$) compared to those who preferred the Cobot. This provides strong evidence that the participants who felt the greatest sense of ownership and control over the autonomous arms were the ones most likely to prefer that system.

Interestingly, no significant difference was found between the groups for the Change in Body Schema sub-scale ($H = 5.31$, $p = 0.0705$), indicating that this aspect of embodiment was not a factor in determining user preference.

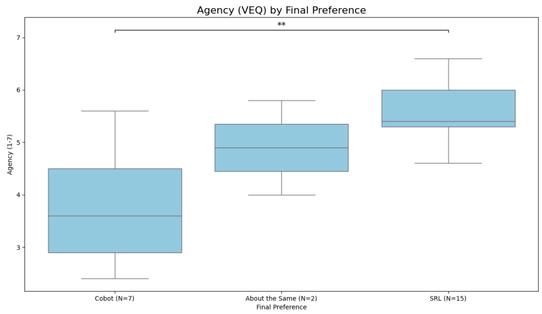
In summary, this analysis demonstrates a clear and statistically significant link between subjective experience and user choice. The preference for the wearable SRL was not arbitrary but was strongly associated with a greater sense of feeling that the arms were their own and that they were in control of the collaborative process.



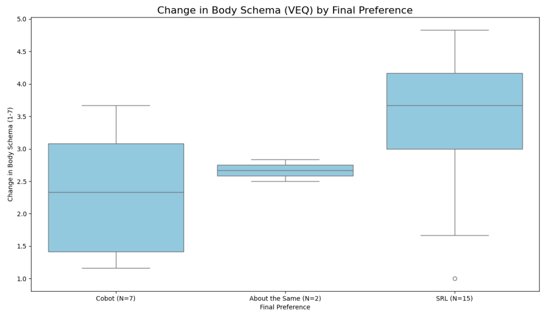

(a) Overall Embodiment




(b) Ownership Sub-scale




(c) Agency Sub-scale




(d) Change in Body Schema Sub-scale

Figure 17: Distribution of VEQ scores for the SRL condition, grouped by participants' final overall preference. The (N=X) in each title indicates the number of participants in that preference group. Asterisks denote the level of statistical significance: $p < 0.1$ (*), $p < 0.05$ (**), $p < 0.01$ (***), $p < 0.001$ (****).

## 5.5 Qualitative Feedback and User Remarks

Qualitative open feedback was also gathered from participants during the post-experiment debriefing to complement the quantitative results. There were various dominant themes which provide additional context for the statistics and insights into the actual user experience.

Many participants addressed the learning and adaptation involved with interaction with the SRL. Several noted that while the wearable arms initially felt somewhat obstructive, especially regarding their position, especially by getting tangled with them, they adapted to the system's autonomous movements over the course of the single trial. For others, this habit led to a strong preference for the SRL, as they began to anticipate its actions and integrate it into their workflow. In contrast, a few participants mentioned that they did not manage to fully get used to the motions by the end of the task, affecting their preference for other conditions. This highlights the importance of training and long-term use in the acceptance of wearable robotic systems.

Another interesting theme was the perception of speed. Some participants described the external Cobot as "slow," even though the FSM logic and action timings were identical for both the SRL and the Cobot. This suggests a potential perceptual effect related to the form factor; because the wearable SRL operates within the user's immediate peripersonal space, its actions of bringing a part to the hand might be perceived as more immediate and faster than those of an external agent.

Finally, one participant provided a counterpoint regarding the clarity of the partner's actions, noting that the Cobot's intentions were easier to understand because its movements were fully contained within their central field of view. In contrast, the SRLs, which are mounted on the user's sides, often operate in the peripheral vision, requiring a different kind of awareness. This feedback underscores a potential trade-off between the close integration of a wearable system and the explicit visibility of an external one.

## 5.6 Limitations and Future Research

While this study provides valuable insights, it is important to acknowledge its limitations. The findings are obtained from a single, well-defined assembly task in a virtual environment, which lacks the haptic feedback and physical strain of a real-world system. Also, the participants were university students who probably have, on average, higher familiarity with technology than the overall population.

Based on these findings and limitations, future research directions may be suggested, in line with the objectives of this thesis:

- **Systematic Evaluation of Control Strategies:** The described VR platform was created to facilitate the comparison of different control interfaces. A pilot study revealed the high cognitive load of a direct manual control scheme, justifying the focus on autonomous systems for the main experiment. An important next step is to use this testing environment to systematically design, implement and test a variety of more intuitive manual and shared-control paradigms that are more intuitive than the autonomous baseline reported here.

- **Exploration of Advanced Autonomous Behaviors:** The current study utilized a scripted FSM for autonomy. Future work should explore more advanced autonomous systems that can learn from and adapt to the user's behavior in real-time. Implementing techniques such as intent recognition or adaptive assistance may result in an even more fluid and collaborative partnership, potentially enhancing the sense of agency.

- **Longitudinal Studies:** This experiment was characterized by a single session. A longitudinal study design, in which participants use the setups over several days, would be invaluable for understanding the long-term effects on learning, skill retention and the development of a deeper, more stable sense of embodiment.

- **Validation with Physical Prototypes:** As a longer-term goal, the most promising control and autonomy paradigms identified within the VR testbed should be implemented and validated on a physical hardware-based system. This would allow for an investigation into the real-world effects of weight, ergonomics and haptic feedback on user performance and experience.

# Chapter 6

# Conclusion

This thesis presented the design, development and evaluation of a modular VR environment created to function as a standardized testbed for research on SRLs. A user study was conducted within this environment to compare unassisted human performance and two distinct modes of autonomous robotic collaboration (a wearable SRL and an external cobot) against each other. This final chapter will briefly summarize the most critical findings, outline the principal contributions of this work and offer a concluding thought on the future of HRI.

## 6.1 Summary of Key Findings

The experimental results showed that the task performance significantly improves when an autonomous robotic partner is present, regardless of the choice of its morphology. Both the wearable SRL and external cobot led to faster and more efficient work.

While both systems were functionally equivalent, the user experience was not identical. The wearable SRL was consistently and significantly perceived as a more animate, intelligent and novel partner than the external cobot. This perception translated into a clear overall preference for the SRL. A correlation analysis also revealed a very important point: this preference was not arbitrary; it was strongly associated with a greater sense of embodiment. Participants who reported higher levels of Ownership and Agency with the SRL were significantly more likely to prefer it, indicating that the subjective feeling of embodiment was a key driver of user satisfaction.

This study also confirmed that users can develop a significant sense of both Ownership and Agency over an autonomous partner, expanding the traditional understanding of embodiment.

## 6.2 Contributions to the Field

This thesis makes several key contributions to the fields of human augmentation and robotics. Methodologically, it provides a validated, modular VR testing viroment that addresses the need for standardized evaluation tools. Empirically, it offers the first direct comparative analysis between a wearable SRL and an external cobot for a collaborative task, proving that the form factor of a robot has a significant impact on the subjective user experience, independent of its performance. Theoretically, the findings on embodiment demonstrate that a sense of agency can exist even without direct motor control, suggesting that predictability and shared intent are important factors in the embodiment of autonomous agents.

## 6.3 Concluding Remarks and Final Thought

The challenge of creating truly seamless robotic assistants not only lies in creating more intelligent and capable autonomous systems, but also in thoughtfully designing the physical and psychological interface between human and machine. The finding that a wearable system was preferred over an equally capable external one suggests that the future of human augmentation may be one where technology becomes less of an external tool and more of an integrated partner. This work provides a robust platform and a set of initial findings to help guide the research community in exploring that future, moving us one step closer to a world where human and robotic capabilities unite in a truly natural and powerful way.

# Bibliography


[1] Dominijanni, G., et al. (2023). *Human motor augmentation with an extra robotic arm without functional interference*. Science Robotics, 8(85), eadh1438. https://doi.org/10.1126/scirobotics.adh1438

[2] Oh, J., et al. (2021). *A 3D head pointer: a manipulation method that enables the spatial position and posture for supernumerary robotic limbs*. ACTA IMEKO, 10(3), 81. https://doi.org/10.21014/acta_imeko.v10i3.1114

[3] Hussain, I., et al. (2017). *A magnetic compatible supernumerary robotic finger for functional magnetic resonance imaging (fMRI) acquisitions: Device description and preliminary results*. 2017 International Conference on Rehabilitation Robotics (ICORR). https://doi.org/10.1109/ICORR.2017.8009409

[4] Jiang, Z., et al. (2023). *A virtual reality platform to evaluate the effects of supernumerary limbs' appearance*. 2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). https://doi.org/10.1109/EMBC40787.2023.10340197

[5] Nishida, N., et al. (2022). *Analysis and Observation of Behavioral Factors Contributing to Improvement of Embodiment to a Supernumerary Limb*. Augmented Humans 2022. https://doi.org/10.1145/3519391.3519413

[6] Sasaki, T., et al. (2016). *Changing body ownership using visual metamorphosis*. Proceedings of the 2016 Virtual Reality International Conference. https://doi.org/10.1145/2927929.2927961

[7] Saberpour Abadian, A., et al. (2023). *Computational Design of Personalized Wearable Robotic Limbs*. Proceedings of the 36th Annual ACM Symposium

on User Interface Software and Technology. https://doi.org/10.1145/3586183.3606748

[8] Maimeri, M., et al. (2019). *Design and Assessment of Control Maps for Multi-Channel sEMG-Driven Prostheses and Supernumerary Limbs*. Frontiers in Neurorobotics, 13, 26. https://doi.org/10.3389/fnbot.2019.00026

[9] Arai, K., et al. (2022). *Embodiment of supernumerary robotic limbs in virtual reality*. Scientific Reports, 12(1), 9769. https://doi.org/10.1038/s41598-022-13981-w

[10] Fukuoka, M., et al. (2019). *FaceDrive: Facial Expression Driven Operation to Control Virtual Supernumerary Robotic Arms*. ICAT-EGVE 2019 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments. https://doi.org/10.2312/EGVE.20191275

[11] Newport, R., et al. (2010). *Fake hands in action: embodiment and control of supernumerary limbs*. Experimental Brain Research, 204(3), 385–395. https://doi.org/10.1007/s00221-009-2104-y

[12] Allemang–Trivalle, A., et al. (2022). *How long does it take to learn trimanual coordination?*. 2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN). https://doi.org/10.1109/RO-MAN53752.2022.9900646

[13] Jing, H., et al. (2023). *Human Operation Augmentation through Wearable Robotic Limb Integrated with Mixed Reality Device*. Biomimetics, 8(6), 479. https://doi.org/10.3390/biomimetics8060479

[14] Huang, Y., et al. (2022). *Human Performance of Three Hands in Unimanual, Bimanual and Trimanual Tasks*. 2022 44th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). https://doi.org/10.1109/EMBC48229.2022.9871248

[15] Sanmartín-Senent, A., et al. (2023). *Redundancy Resolution in Trimanual vs. Bimanual Tracking Tasks*. 2023 45th Annual International Conference of the

IEEE Engineering in Medicine & Biology Society (EMBC). https://doi.org/10.1109/EMBC40787.2023.10340722

[16] Drogemuller, A., et al. (2019). *Remapping a Third Arm in Virtual Reality*. 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). https://doi.org/10.1109/VR.2019.8798197

[17] Cadete, D., & Longo, M. R. (2022). *The long sixth finger illusion: The representation of the supernumerary finger is not a copy and can be felt with varying lengths*. Cognition, 218, 104948. https://doi.org/10.1016/j.cognition.2021.104948

[18] Rosa, N., et al. (2019). *The Supernumerary Hand Illusion in Augmented Reality*. ACM Transactions on Applied Perception, 16(2), 1–20. https://doi.org/10.1145/3341225

[19] Molnar, J., & Menguc, Y. (2022). *Toward Handling the Complexities of Non-Anthropomorphic Hands*. CHI Conference on Human Factors in Computing Systems Extended Abstracts. https://doi.org/10.1145/3491101.3519871

[20] Huang, Y., et al. (2021). *Trimanipulation: Evaluation of human performance in a 3-handed coordination task*. 2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC). https://doi.org/10.1109/SMC52423.2021.9659027

[21] Li, H.-B., et al. (2023). *Wearable Extra Robotic Limbs: A Systematic Review of Current Progress and Future Prospects*. Journal of Intelligent & Robotic Systems, 109(1), 16. https://doi.org/10.1007/s10846-023-01940-0

[22] Yamamura, N., et al. (2023). *Social Digital Cyborgs: The Collaborative Design Process of JIZAI ARMS*. Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3544548.3581169

[23] Schrepp, M., Hinderks, A., & Thomaschewski, J. (2017). *Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S)*. International Journal of Interactive Multimedia and Artificial Intelligence, 4(6), 103. https://doi.org/10.9781/ijimai.2017.09.001

[24] Cheymol, A., et al. (2023). *Beyond my Real Body: Characterization, Impacts, Applications and Perspectives of "Dissimilar" Avatars in Virtual Reality*. IEEE Transactions on Visualization and Computer Graphics, 29(11), 4426–4437. https://doi.org/10.1109/TVCG.2023.3320209

[25] Roth, D., & Latoschik, M. E. (2020). *Construction of the Virtual Embodiment Questionnaire (VEQ)*. IEEE Transactions on Visualization and Computer Graphics, 26(12), 3546–3556. https://doi.org/10.1109/TVCG.2020.3023603

[26] Kawamura, K. (2023). *Gaze-Driven Implicit Assistive Control for Parallel Robot Arms in Distributed Environments* (Unpublished Master's thesis). Keio University, Graduate School of Science and Technology, Yokohama, Japan.

[27] Kitchenham, B., & Charters, S. (2007). *Guidelines for performing Systematic Literature Reviews in Software Engineering*. EBSE Technical Report EBSE-2007-01, Keele University.

[28] Arents, J., et al. (2021). *Human–Robot Collaboration Trends and Safety Aspects: A Systematic Review*. Journal of Sensor and Actuator Networks, 10(3), 48. https://doi.org/10.3390/jsan10030048

[29] Apraiz, A., Lasa, G., & Mazmela, M. (2023). *Evaluation of User Experience in Human–Robot Interaction: A Systematic Literature Review*. International Journal of Social Robotics, 15(2), 187–210. https://doi.org/10.1007/s12369-022-00957-z

[30] Petkova, V. F., & Slater, M. (2009). *A 'body in a room' illusion: the feeling of presence in virtual reality depends on self-location in the virtual body*. CyberPsychology & Behavior, 12(5), 567–571. https://doi.org/10.1089/cpb.2009.0008

[31] Slater, M., Perez-Marcos, D., Ehrsson, H. H., & Sanchez-Vives, M. V. (2008). *Body ownership in a virtual reality mirror*. PLoS one, 3(12), e3831. https://doi.org/10.1371/journal.pone.0003831

[32] Biocca, F. (1997). *Being there: The subjective experience of presence in virtual environments*. In F. Biocca & M. R. Levy (Eds.), *Communication in the age of virtual reality* (pp. 5–45). Lawrence Erlbaum Associates, Inc.

[33] Botvinick, M., & Cohen, J. (1998). *Rubber hands 'feel' touch that eyes see.* Nature, 391(6669), 756. https://doi.org/10.1038/35784

[34] Yee, N., & Bailenson, J. (2007). *The Proteus Effect: The Effect of Transformed Self-Representation on Behavior*. Human Communication Research, 33(3), 271–290. https://doi.org/10.1111/j.1468-2958.2007.00299.x

[35] Ballesteros, E., Man, B., & Asada, H. H. (2023). *Supernumerary Robotic Limbs for Next Generation Space Suit Technology*. In 2023 IEEE International Conference on Robotics and Automation (ICRA) (pp. 7519–7525). London, United Kingdom. https://doi.org/10.1109/ICRA48891.2023.10161579

[36] Ballesteros, E., et al. (2024). *Supernumerary Robotic Limbs to Support Post-Fall Recoveries for Astronauts*. In 2024 IEEE International Conference on Robotics and Automation (ICRA) (pp. 2324–2331). Yokohama, Japan. https://doi.org/10.1109/icra57147.2024.10610849

[37] Wideström, J., et al. (2000). *The collaborative cube puzzle: a comparison of virtual and real environments*. In Proceedings of the third international conference on Collaborative virtual environments (pp. 165–171). https://doi.org/10.1145/351006.351035

[38] Yoon, B., et al. (2019). *The Effect of Avatar Appearance on Social Presence in an Augmented Reality Remote Collaboration*. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR). https://doi.org/10.1109/vr.2019.8797719

[39] Bartneck, C., et al. (2009). *Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots*. International Journal of Social Robotics, 1(1), 71–81. https://doi.org/10.1007/s12369-008-0001-3

[40] Steed, A., et al. (1999). *Leadership and collaboration in shared virtual environments*. In Proceedings IEEE Virtual Reality 1999. https://doi.org/10.1109/vr.1999.756941

[41] Hart, S. G., & Staveland, L. E. (1988). *Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research.* In P. A. Hancock & N. Meshkati (Eds.), Human mental workload (pp. 139–183). North-Holland Press.

[42] Recursoft. (2025). *Logic Driver Lite* (Version 1.6.1) [Unreal Engine Plugin]. Fab, from https://www.fab.com/listings/e7500c39-5b12-4b88-aac2-12b14c0b1387

[43] Treshchev, G. (2024). *Runtime Speech Recognizer* (Version 1.0) [Unreal Engine Plugin]. GitHub, from https://github.com/gtreshchev/RuntimeSpeechRecognizer

[44] Epic Games, Inc. (2024). *JSON Blueprint Utilities* (Version 1.0) [Unreal Engine Plugin]. Fab, from https://www.fab.com/it/listings/225ae012-0ce9-484b-91f1-9871bbac3a58

# Appendix A

## A.1 Questionnaire Instruments

Table 7: Participant Demographics and Experience Questionnaire.

| No. | Question |
|---|---|
| 1 | How old are you?<br>*(Response: Open numerical input)* |
| 2 | What is your gender?<br>*(Response: Open text input)* |
| 3 | Are you right handed?<br>*(Response: Multiple choice [Right / Left])* |
| 4 | How often do you experience virtual reality?<br>*(Response: Multiple choice [Never / Once or twice a year / etc.])* |
| 5 | How often do you play video games?<br>*(Response: Multiple choice [Never / Once or twice a year / etc.])* |
| 6 | How often have you operated or controlled a physical or virtual robot?<br>*(Response: Multiple choice [Never / Once or twice in my life / etc.])* |

Table 8: NASA Task Load Index (NASA-TLX) Sub-scales. For each dimension, participants provided a rating on a 21-point scale ranging from 1 (Very Low) to 21 (Very High).

| **Dimension** | **Description** |
|---|---|
| Mental Demand | How mentally demanding was the task? |
| Physical Demand | How physically demanding was the task? |
| Temporal Demand | How hurried or rushed was the pace of the task? |
| Performance | How successful were you in accomplishing what you were asked to do? |
| Effort | How hard did you have to work to accomplish your level of performance? |
| Frustration | How insecure, discouraged, irritated, stressed, and annoyed were you? |

Table 9: User Experience Questionnaire - Short (UEQ-S). Participants rated each item on a 7-point semantic differential scale.

| **UEQ-S Items** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| obstructive | 1 | 2 | 3 | 4 | 5 | 6 | 7 | supportive |
| complicated | 1 | 2 | 3 | 4 | 5 | 6 | 7 | easy |
| inefficient | 1 | 2 | 3 | 4 | 5 | 6 | 7 | efficient |
| confusing | 1 | 2 | 3 | 4 | 5 | 6 | 7 | clear |
| boring | 1 | 2 | 3 | 4 | 5 | 6 | 7 | exciting |
| uninteresting | 1 | 2 | 3 | 4 | 5 | 6 | 7 | interesting |
| conventional | 1 | 2 | 3 | 4 | 5 | 6 | 7 | inventive |
| usual | 1 | 2 | 3 | 4 | 5 | 6 | 7 | leading edge |

Table 10: Virtual Embodiment Questionnaire (VEQ) for the SRL Condition. All items were rated on a 7-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree).

| **No.** | **Question** |
|---|---|
| **Section 1: Ownership** | |

**Table 10 – continued from previous page**

| No. | Question |
|---|---|
| 1 | It felt like the extra robotic arms were my body. |
| 2 | It felt like the components of the extra robotic arms (e.g., hands, forearms) were my body parts. |
| 3 | The extra robotic arms felt like they were part of a human body. |
| 4 | I felt like the extra robotic arms belonged to someone else. (*reverse scored) |
| 5 | It felt like the extra robotic arms belonged to me. |
| **Section 2: Agency** | |
| 6 | The movements of the extra robotic arms felt like they were my movements. |
| 7 | I enjoyed controlling the extra robotic arms. |
| 8 | I felt like I was controlling the movements of the extra robotic arms. |
| 9 | I felt like I was causing the movements of the extra robotic arms. |
| 10 | The movements of the extra robotic arms were in sync with my own intentions. |
| **Section 3: Change in Perceived Body Schema** | |
| 11 | I had the illusion of having a different body to my own. |
| 12 | I felt like the form or appearance of my own body had changed. |
| 13 | I felt like I had to check that my own body still looked like I remembered. |
| 14 | I felt like the weight of my own body had changed. |
| 15 | I felt like the size (height) of my own body had changed. |
| 16 | I felt like the width of my own body had changed. |

Table 11: Collaborative Task Experience Questionnaire. Section A and B items were rated on a 7-point Likert scale. Section C items were rated on a 5-point semantic differential scale.

| No. | Question / Item |
|---|---|
| **Section A: Collaboration Quality** | |
| *(1 = Not at all, 7 = To a great extent)* | |
| 1 | To what extent did you experience that you and your partner were collaborating? |
| 2 | To what extent did you feel your partner was cooperative? |
| *(1 = Strongly Disagree, 7 = Strongly Agree)* | |
| 3 | I enjoyed the collaboration with my partner. |
| **Section B: Sense of Co-Presence** | |
| *(1 = Not at all, 7 = To a great extent)* | |
| 4 | To what extent did you have a sense of being with your partner? |
| 5 | To what extent were you able to forget about your partner and just concentrate on the task? (*reverse scored) |
| **Section C: Partner Attributes (Godspeed)** | |
| *Anthropomorphism* | |
| | Fake 1 2 3 4 5 Natural |
| | Machinelike 1 2 3 4 5 Humanlike |
| | Unconscious 1 2 3 4 5 Conscious |
| | Artificial 1 2 3 4 5 Lifelike |
| | Moving rigidly 1 2 3 4 5 Moving elegantly |
| *Animacy* | |
| | Dead 1 2 3 4 5 Alive |
| | Stagnant 1 2 3 4 5 Lively |
| | Mechanical 1 2 3 4 5 Organic |
| | Artificial 1 2 3 4 5 Lifelike |

**Table 11 – continued from previous page**

| No. | Question / Item |
|---|---|
| | Inert 1 2 3 4 5 Interactive |
| | Apathetic 1 2 3 4 5 Responsive |
| *Likeability* | |
| | Dislike 1 2 3 4 5 Like |
| | Unfriendly 1 2 3 4 5 Friendly |
| | Unkind 1 2 3 4 5 Kind |
| | Unpleasant 1 2 3 4 5 Pleasant |
| | Awful 1 2 3 4 5 Nice |
| *Perceived Intelligence* | |
| | Incompetent 1 2 3 4 5 Competent |
| | Ignorant 1 2 3 4 5 Knowledgeable |
| | Irresponsible 1 2 3 4 5 Responsible |
| | Unintelligent 1 2 3 4 5 Intelligent |
| | Foolish 1 2 3 4 5 Sensible |
| *Perceived Safety* | |
| | Anxious 1 2 3 4 5 Relaxed |
| | Calm 1 2 3 4 5 Agitated |
| | Still 1 2 3 4 5 Surprised |

Table 12: Post-Experiment Preference Questionnaire. Questions 1-3 were multiple choice. Question 4 required participants to rank the three conditions from 1 (most preferred) to 3 (least preferred).

| No. | Question |
|---|---|
| **Forced-Choice Preference** | |
| 1 | Which robotic partner did you feel you were "doing something together" with the most?<br>*(Response options: SRL / Cobot / About the Same)* |
| 2 | Which robotic partner gave you a stronger sense of "being with you"?<br>*(Response options: SRL / Cobot / About the Same)* |
| 3 | Overall, which robotic partner did you prefer collaborating with?<br>*(Response options: SRL / Cobot / About the Same)* |
| **Overall Condition Ranking** | |
| 4 | Please order the conditions based on your preference (1 = most preferred, 3 = least preferred):<br>___ *Natural Arms (Solo)*<br>___ *SRL Collaboration*<br>___ *Cobot Collaboration* |

## A.2 Detailed Statistical Results

Table 15: Pairwise t-test Comparisons of UEQ-S Items Across Conditions (with Holm–Bonferroni correction)

| UEQ-S Scale | Comparison | t-statistic | p-value | Significant |
|---|---|---|---|---|
| **Overall UX Score** | | | | |
| *Overall Score* | Solo vs. SRL | -10.156 | $< 0.0001$ | **Yes** |
| | Solo vs. Cobot | -10.077 | $< 0.0001$ | **Yes** |

**Table 15 – continued from previous page**

| UEQ-S Scale | Comparison | t-statistic | p-value | Significant |
|---|---|---|---|---|
| | SRL vs. Cobot | 1.653 | 0.1119 | No |
| **Pragmatic Quality** | | | | |
| *Overall Score* | Solo vs. SRL | -6.449 | $< 0.0001$ | **Yes** |
| | Solo vs. Cobot | -8.247 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | 0.000 | 1.0000 | No |
| *Individual Items* | | | | |
| 1. Obstructive vs. Supportive | Solo vs. SRL | -8.033 | $< 0.0001$ | **Yes** |
| | Solo vs. Cobot | -8.536 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | 0.654 | 0.5194 | No |
| 2. Complicated vs. Easy | Solo vs. SRL | -4.699 | 0.0002 | **Yes** |
| | Solo vs. Cobot | -5.171 | 0.0001 | **Yes** |
| | SRL vs. Cobot | 0.000 | 1.0000 | No |
| 3. Inefficient vs. Efficient | Solo vs. SRL | -5.665 | $< 0.0001$ | **Yes** |
| | Solo vs. Cobot | -6.763 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | -0.327 | 0.7466 | No |
| 4. Confusing vs. Clear | Solo vs. SRL | -3.890 | 0.0015 | **Yes** |
| | Solo vs. Cobot | -5.627 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | -0.473 | 0.6410 | No |
| **Hedonic Quality** | | | | |
| *Overall Score* | Solo vs. SRL | -11.807 | $< 0.0001$ | **Yes** |
| | Solo vs. Cobot | -8.835 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | 2.963 | 0.0070 | **Yes** |
| *Individual Items* | | | | |
| 5. Boring vs. Exciting | Solo vs. SRL | -7.240 | $< 0.0001$ | **Yes** |
| | Solo vs. Cobot | -6.802 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | 1.592 | 0.1251 | No |
| 6. Uninteresting vs. Interesting | Solo vs. SRL | -6.482 | $< 0.0001$ | **Yes** |

**Table 15 – continued from previous page**

| UEQ-S Scale | Comparison | t-statistic | p-value | Significant |
|---|---|---|---|---|
| | Solo vs. Cobot | -5.689 | < 0.0001 | **Yes** |
| | SRL vs. Cobot | 1.551 | 0.1345 | No |
| 7. Conventional vs. Inventive | Solo vs. SRL | -11.132 | < 0.0001 | **Yes** |
| | Solo vs. Cobot | -7.620 | < 0.0001 | **Yes** |
| | SRL vs. Cobot | 3.542 | 0.0017 | **Yes** |
| 8. Usual vs. Leading Edge | Solo vs. SRL | -13.446 | < 0.0001 | **Yes** |
| | Solo vs. Cobot | -8.886 | < 0.0001 | **Yes** |
| | SRL vs. Cobot | 3.037 | 0.0059 | **Yes** |

Table 16: Pairwise t-test Comparisons for the Collaborative Task Experience Questionnaire (SRL vs. Cobot) (with Holm–Bonferroni correction)

| Scale | Item / Sub-scale | t-statistic | p-value | Significant |
|---|---|---|---|---|
| **Collaboration & Co-Presence** | | | | |
| Collaboration | ...were collaborating? | 1.334 | 0.1952 | No |
| Cooperation | ...was cooperative? | -0.253 | 0.8024 | No |
| Enjoyment | I enjoyed the collaboration... | 0.440 | 0.6643 | No |
| Co-Presence | ...sense of being with partner? | -1.737 | 0.0958 | No |
| Co-Presence | ...forget about partner? (rev) | 0.902 | 0.3765 | No |
| **Godspeed: Anthropomorphism** | | | | |
| *Overall Score* | | **2.621** | **0.0153** | **Yes** |
| | Fake vs. Natural | 1.801 | 0.0849 | No |
| | Machinelike vs. Humanlike | 2.530 | 0.0187 | **Yes** |
| | Unconscious vs. Conscious | 1.599 | 0.1236 | No |
| | Artificial vs. Lifelike | 3.191 | 0.0041 | **Yes** |
| | Moving rigidly vs. Moving elegantly | 0.450 | 0.6570 | No |
| **Godspeed: Animacy** | | | | |

**Table 16 – continued from previous page**

| Scale | Item / Sub-scale | t-statistic | p-value | Significant |
|---|---|---|---|---|
| *Overall Score* | | **4.793** | **0.0001** | **Yes** |
| | Dead vs. Alive | 2.532 | 0.0186 | **Yes** |
| | Stagnant vs. Lively | 2.917 | 0.0078 | **Yes** |
| | Mechanical vs. Organic | 3.703 | 0.0012 | **Yes** |
| | Artificial vs. Lifelike | 2.122 | 0.0448 | **Yes** |
| | Inert vs. Interactive | 4.628 | 0.0001 | **Yes** |
| | Apathetic vs. Responsive | 4.511 | 0.0002 | **Yes** |
| **Godspeed: Likeability** | | | | |
| *Overall Score* | | **1.809** | **0.0836** | **No** |
| | Dislike vs. Like | 0.894 | 0.3804 | No |
| | Unfriendly vs. Friendly | 2.066 | 0.0503 | **Marginally** |
| | Unkind vs. Kind | 1.772 | 0.0897 | No |
| | Unpleasant vs. Pleasant | 1.446 | 0.1617 | No |
| | Awful vs. Nice | 1.446 | 0.1617 | No |
| **Godspeed: Perceived Intelligence** | | | | |
| *Overall Score* | | **2.716** | **0.0123** | **Yes** |
| | Incompetent vs. Competent | 2.541 | 0.0183 | **Yes** |
| | Ignorant vs. Knowledgeable | 3.093 | 0.0051 | **Yes** |
| | Irresponsible vs. Responsible | 0.617 | 0.5430 | No |
| | Unintelligent vs. Intelligent | 2.122 | 0.0448 | **Yes** |
| | Foolish vs. Sensible | 1.621 | 0.1186 | No |
| **Godspeed: Perceived Safety** | | | | |
| *Overall Score* | | **0.594** | **0.5581** | No |
| | Anxious vs. Relaxed | 1.430 | 0.1661 | No |
| | Calm vs. Agitated | 0.778 | 0.4445 | No |
| | Still vs. Surprised | -0.811 | 0.4259 | No |

Table 13: Summary of One-Way ANOVA for UEQ-S Items Across Conditions

| **UEQ-S Item** | **F-statistic** | **p-value** |
|---|---|---|
| 1. Obstructive vs. Supportive | 37.791 | $< 0.0001$ |
| 2. Complicated vs. Easy | 19.397 | $< 0.0001$ |
| 3. Inefficient vs. Efficient | 32.755 | $< 0.0001$ |
| 4. Confusing vs. Clear | 14.916 | $< 0.0001$ |
| 5. Boring vs. Exciting | 20.737 | $< 0.0001$ |
| 6. Uninteresting vs. Interesting | 18.882 | $< 0.0001$ |
| 7. Conventional vs. Inventive | 48.304 | $< 0.0001$ |
| 8. Usual vs. Leading Edge | 68.594 | $< 0.0001$ |

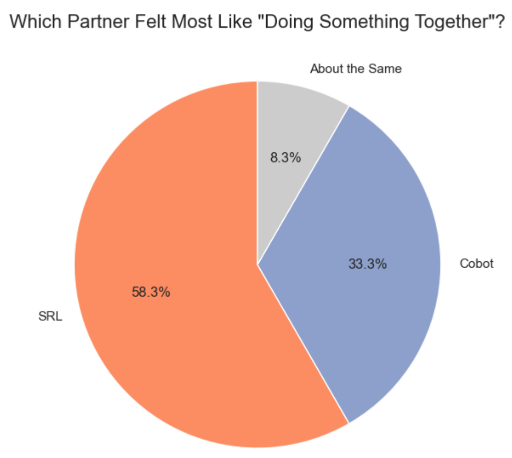



Figure 18: Participant responses to the question: "Which robotic partner did you feel you were 'doing something together' with the most?"

Table 14: Pairwise t-test Comparisons of NASA-TLX Sub-scales Across Conditions (with Holm–Bonferroni correction)

| **Workload Dimension** | **Comparison** | **t-statistic** | **p-value** | **Significant** |
|---|---|---|---|---|
| **Raw TLX** | Solo vs. Cobot | 5.425 | $< 0.0001$ | **Yes** |
| | Solo vs. SRL | 6.211 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | -0.205 | 0.8397 | No |
| **Mental Demand** | Solo vs. Cobot | 4.716 | 0.0003 | **Yes** |
| | Solo vs. SRL | 4.417 | 0.0004 | **Yes** |
| | SRL vs. Cobot | -0.159 | 0.8750 | No |
| **Physical Demand** | Solo vs. Cobot | 3.905 | 0.0014 | **Yes** |
| | Solo vs. SRL | 5.127 | 0.0001 | **Yes** |
| | SRL vs. Cobot | -1.419 | 0.1694 | No |
| **Effort** | Solo vs. Cobot | 6.031 | $< 0.0001$ | **Yes** |
| | Solo vs. SRL | 8.626 | $< 0.0001$ | **Yes** |
| | SRL vs. Cobot | -1.330 | 0.1967 | No |
| **Frustration** | Solo vs. Cobot | 4.625 | 0.0004 | **Yes** |
| | Solo vs. SRL | 3.651 | 0.0027 | **Yes** |
| | SRL vs. Cobot | 0.758 | 0.4562 | No |
| **Temporal Demand** | Solo vs. Cobot | 0.899 | 0.7558 | No |
| | Solo vs. SRL | -0.596 | 0.7558 | No |
| | SRL vs. Cobot | 2.619 | 0.0460 | **Yes** |
| **Performance** | Solo vs. Cobot | -2.860 | 0.0265 | **Yes** |
| | Solo vs. SRL | -2.002 | 0.1145 | No |
| | SRL vs. Cobot | -0.651 | 0.5212 | No |

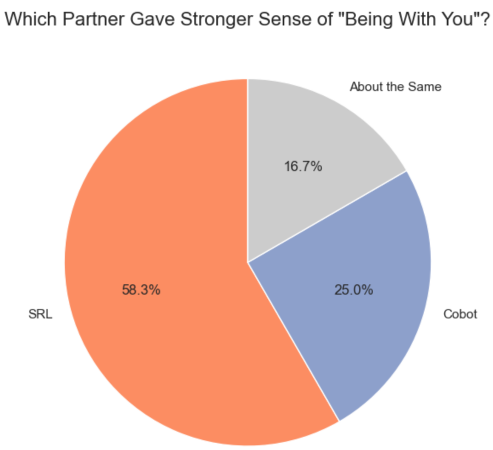



Figure 19: Participant responses to the question: "Which robotic partner gave you a stronger sense of 'being with you'?"

## A.3 Details of FSM for Autonomous SRL & Cobot

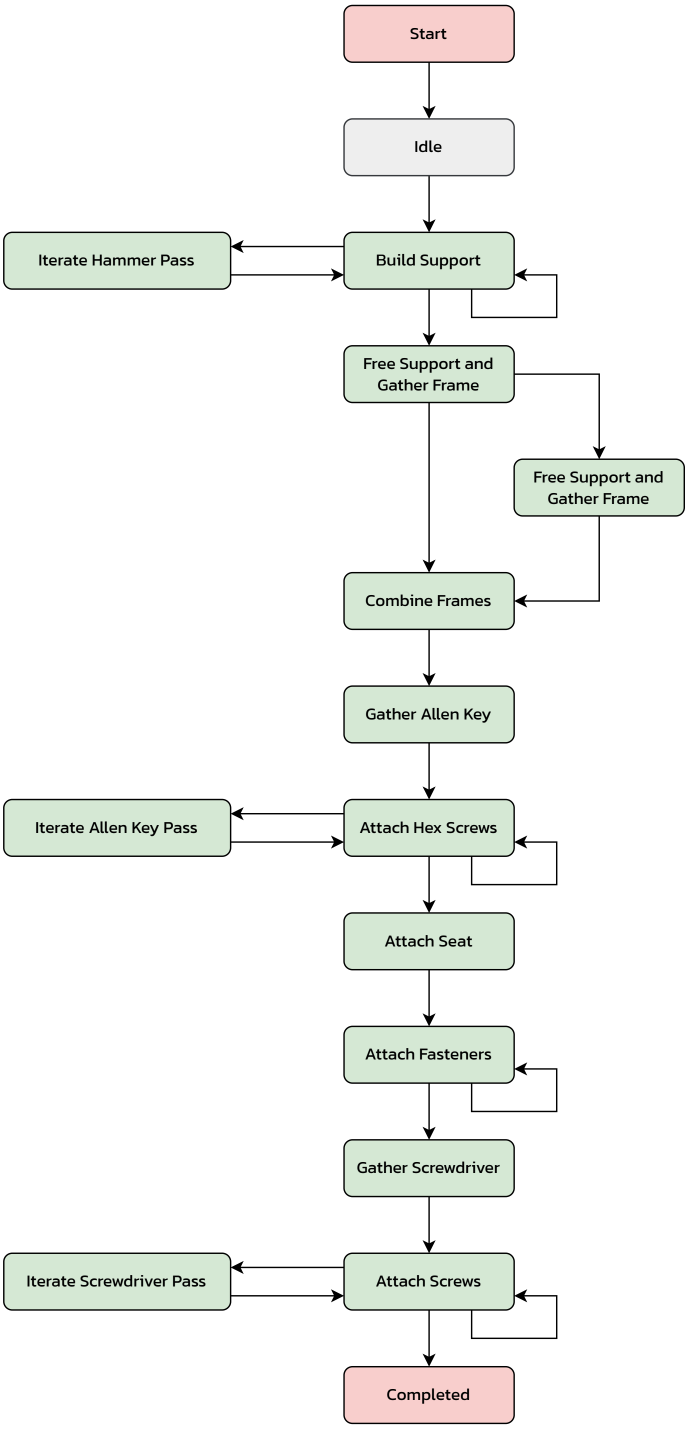



Figure 20: FSM.

## A.4 Sample JSON Data Output Structure


```
{
        "hand_L_N_Grab": 30,
        "hand_R_N_Grab": 62,
        "sRL_L_N_Grab": 26,
        "sRL_R_N_Grab": 7,
        "hand_L_3DPath": {
                "time": [
                        15.979,
                        15.985,
                        15.998,
                        "...",
                        219.054
                ],
                "path": [
                        { "x": 84.089, "y": 5.838, "z": 141.798 },
                        { "x": 84.027, "y": 5.817, "z": 141.784 },
                        { "x": 83.993, "y": 5.767, "z": 141.734 },
                        "...",
                        { "x": -30.701, "y": 2.267, "z": 2.457 }
                ]
        },
        "hand_R_3DPath": { "...": "..." },
        "sRL_L_3DPath": { "...": "..." },
        "sRL_R_3DPath": { "...": "..." },
        "sRL_L_Idle": 0.234,
        "sRL_R_Idle": 0.147,
        "n_Drops": 1,
        "headTurnAngles": [
                0,
                -1.607,
                -1.828,
                "...",
                0.260
        ],
        "timeStamps": [
                15.970,
                71.511,
```

```
                88.370,
                156.438,
                219.070
        ],
        "solo": false,
        "task": 0,
        "cobot": true
}
```

Listing A.1: Example JSON file structure.