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Simon RICHIR and the Doctoral Consortium Committee

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Exploring the potential of the Industrial Metaverse in Systems Engineering: hope beyond the hype?

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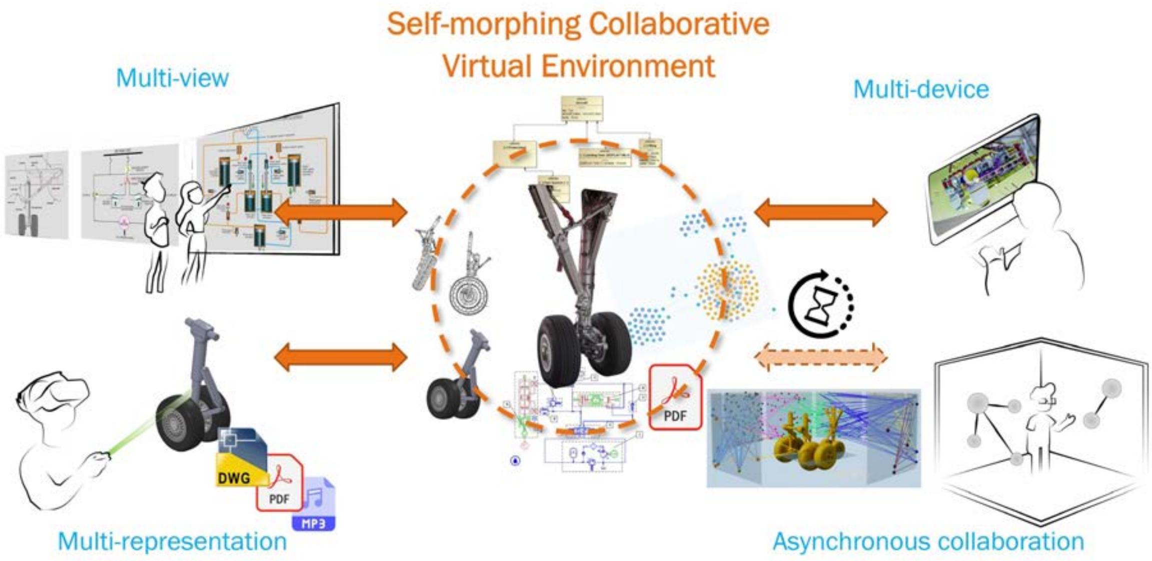

Figure 1: Conceptual Representation of Self-Morphing Collaborative Virtual Environment Mechanics.

Abstract

Collaborative Virtual Environments (CVEs) with adaptive mechanisms are essential for addressing the complexity of engineered systems design tasks involving a multidisciplinary team of experts modeling different views of the system with their preferred visual metaphors and devices. This research focuses on self-morphing CVEs with three key features: multi-view, multi-representation, and multi-device for visualization and interaction. This Ph.D. thesis aims to conceptualize, demonstrate, and evaluate a self-morphing CVE that supports synchronous and asynchronous collaborative systems architecture tasks. This position paper invites discussion on metrics for assessing adaptive CVEs and the impact of device-specific features on collaboration during system modeling activities.

1 Introduction

Modern systems are becoming more complex, integrating people, technologies, hardware, software, processes, and enterprises. This complexity demands intelligent and intuitive model-based system engineering (SE) techniques Ramos et al. (2011). As data complexity rises, traditional 2D displays become inefficient due to their limited size and resolution. To address these limitations, researchers have explored advanced visualization devices, such as head-mounted displays (HMDs), wall-sized displays, and Cave Automatic Virtual Environment (CAVE) systems, which expand human-computer interaction and bring new data visualization possibilities. The interoperability of heterogeneous visualization and interaction devices requires adapting the 3D user interface to them, the user and the task. These adaptation capabilities are gathered under the concept of self-morphing CVE.

A CVE becomes self-morphing when it adapts its 3D user interface to the user's device, domain-specific concerns, and tasks Seidl and Zschaler (2018). For example, some engineers prefer symbolic 2D schematics, while others may need high-fidelity 3D models. A self-morphing CVE automatically renders or transforms the displayed information to suit each participant's needs, thereby improving design coherence and coordination.

2 Research problem

Regarding the flexibility of the CVE in multidisciplinary design activities, two central concepts are multi-view and multi-representation, as illustrated in 1.

A view is a set of concerns regarding the system under design. Multi-view integrates diverse user concerns on the same system-of-interest into a unified, holistic view. For example, when looking at a landing gear, a mechanical engineer is concerned about its structure, a systems engineer analyses its use cases and requirements, whereas a hydraulic engineer is concerned about its hydraulic circuit and failure modes, respectively. The final goal is to ensure consistency among all the views.

Multi-representation is the ability to visually encode the same engineering artifact with various representations so that users can select the one that suits their view. For example, a stakeholder interested in the structural view of the landing gear system could flexibly switch between a 3D model, a 2D box-and-arrow diagram, an image, a symbol, a hand-free sketch, a text, [. . .], or a voice recording. The ultimate goal is to enable all stakeholders to communicate with their vernacular graphical representations rather than vehicular ones.

The most appropriate representation depends on the user's view a stakeholder has on the system and the devices used to interact and visualize the representation. For example, Cavallo et al. (2019) showed that with a wall-sized display, a user tends to less explore the virtual environment compared to an HMD. Integrating heterogeneous devices into a CVE is commonly referred to as Asymmetric Collaboration. IBM's Dataspace project exemplifies this approach, creating a room-sized collaboration environment where people can interact with 2D and 3D metaphors. This setup combines movable high-resolution displays, an interactive projection table, and augmented and virtual reality head-mounted displays Cavallo et al. (2019). This thesis will concentrate on synchronous collaboration through an HMD, Desktop PC, wall-sized display, and asynchronous collaboration through a CAVE.

Adaptation also applies to the collaborative task a multidisciplinary design team attempts to achieve. A self-adaptive CVE should implement mechanisms to adjust the

3D user interface to each designer's habit and intent according to the task.

However, despite the potential of these CVEs in collaborative mediated design, there is a gap in the system's ability to offer adaptive mechanisms that address the domain-specific views of different users involved in a particular design task.

3 Research focus and expected contributions

The current scope of this PhD thesis, is voluntarily broad to learn the essence of the domain before refining the research questions and hypotheses. The initial general research question is the following.

- **How can a collaborative adaptive virtual environment impact asymmetric collaboration during system architecture design tasks?**

Collaboration is a critical aspect of this research. We began reviewing existing studies on asymmetric collaboration, explicitly focusing on computer-mediated collaborative design activities. We aim to investigate the dimensions of collaboration influenced by adaptive CVE and their potential to enhance multidisciplinary preliminary design activities. Specifically, we intend to address two key questions:

- *How do different representations (e.g., 2D diagrams, 3D models, symbolic abstractions) support the evolving interests of heterogeneous stakeholders—each bringing distinct domain-specific concerns and preferred interaction devices—while ensuring consistency and shared understanding in complex system architecting tasks?*
- *Which adaptive mechanisms most effectively adapt these domain-specific representations to each stakeholder's roles, responsibilities, and visualization devices (e.g., VR HMDs, wall-sized displays, desktop PCs, CAVEs), and how do these adaptations influence collaboration dynamics, decision-making quality, and overall design performance in an asymmetric environment?*

3.1 Scientific Contribution

The expected scientific contribution is understanding how an adaptive CVE impacts collaborative design activities a multidisciplinary team performs. Controlled experiments will be conducted to understand how adaptation parameters can influence collaborative design performances individually or in combination. The choice of the CVE's adaptation parameters and the dimensions of collaboration that will be studied requires a more in-depth literature review.

3.2 Practical Contribution

This expected practical contribution is conceptualizing, designing, developing, and validating an adaptive CVE that will be integrated into the SKYREAL commercial software suite. We will focus on synchronous collaboration between HMD, wall-sized display, desktop PC, and asynchronous collaboration with a CAVE. Among the practical applications, we plan to use the adaptive CVE with a group of volunteer participants involved in a complex system architecting case study. All activities will be performed in the virtual world to demonstrate what an industrial metaverse in complex systems architecting could look like.

4 Research progress

Table 1: Review of adaptive capabilities in CVEs.

Authors	**Symmetric**	**Asymmetric**	**Multi-view**	**Multi-representation**	**User profile**	**Visualization**	**Task**
Febretti et al. (2013)	x	-	-	x	-	x	-
Febretti et al. (2014)	-	x	x	-	-	-	-
Ibayashi et al. (2015)	-	x	x	x	x	x	-
Le Chenechal et al. (2015)	-	x	x	-	-	x	x
Grandi et al. (2019)	x	x	-	x	-	x	x
Cavallo et al. (2019)	-	x	x	-	-	x	-
Tong et al. (2023)	x	x	x	-	-	x	x

We started the literature review by focusing on CVEs implementations, emphasizing their type of collaboration: symmetric and asymmetric. The review also examines multi-view capabilities, multi-representation options, and self-morphism divided into user profile adaptation, visualization adaptability, and task-specific customization. This analysis aims to identify gaps in current systems and provide valuable information for developing more adaptive CVEs.

Table 1 highlights a strong interest in asymmetric CVEs without exploring adaptation parameters, meaning the 3D UI remains the same for all users with different concerns and profiles interacting with different devices. This gap presents valuable opportunities for further research and contributions. Recent studies Tong et al. (2023) on PC-VR asymmetric collaboration started to discuss these issues. Authors emphasize the importance of adaptive user interfaces and content, revealing that a ”mirrored VR” interface—designed to mimic PC interaction in VR—can constrain the potential of each platform Tong et al. (2023)

Ibayashi et al. (2015), and Le Chenechal et al. (2015), both illustrate how asymmetric collaboration can be fostered in architectural design by combining a top-down, table-based viewpoint for designers with an immersive, first-person HMD viewpoint for occupants. These approaches address critical aspects such as user-awareness, viewpoint asymmetry, and differentiated interaction modes. Moreover, they highlight the need for a flexible virtual environment that can adapt to each user's device, role, and interaction int a multidisciplinary teams.

5 Conclusion

This research addresses a gap in the design of CVEs by introducing adaptive mechanisms. The systematic literature review will continue to discuss the following questions during the doctoral consortium.

- What are the most influential metrics for assessing the impact of an adaptive CVE on collaboration and task performance?
- How does using a specific device (e.g., VR HMD, PC, wall-sized display, CAVE) and its intrinsic features and interaction modes influence the distribution of roles and responsibilities during a collaboration task?

By addressing these questions, this research aims to frame its investigation and expand its understanding of collaboration and the impact of adaptive mechanisms.

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The Role of Telepresence in Consumer Environmental Responsibility: The Case of Virtual Reality Educational Experiences

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1 Introduction

For several years now, degradation of the planet presents significant challenges (IPCC, 2023), but the commitment of the general public to preserving our natural environment is still insufficient. Particularly because environmental issues can sometimes seem complex and remote (Lorenzoni, Nicholson-Cole and Whitmarsh, 2007). Environmental concern (EC) are the subject of research in all disciplines, including management sciences to develop effective solutions to help us meet today's climate challenges. Our research examines at the effects of telepresence in a virtual reality (VR) educational experiences on adopting Pro-Environmental Behaviours (PEB). We will explore the mediating role of emotions and perceived environmental risk by considering two of its dimensions: susceptibility and severity. We will also analyse the moderating role of psychological distance.

1.1 Interest in the Subject and Research Objectives

The expected theoretical, managerial and societal benefits of this research are manifold. Firstly, this study aims to consolidate and enrich the determinants that promote PEB, by measuring and analysing (a) the effect of the immersive nature of an educational experience (2D vs. VR), and (b) the effect of message framing (near vs. far) on telepresence. We will analyse the effects of telepresence on pro-environmental intentions and behaviours. Two mediators will be studied: emotions and perceived risk. Finally, we observe the moderating role of psychological distance in this relationship. Thus, this study aims to better appreciate the benefits and limitations of these new educational VR experiences in PEB adoption. To this end, a set of recommendations and methods will be proposed for managers and content creators to support them in their decision-making.

1.2 Issues and Research Questions

We will attempt to answer the following research questions - To what extent...

- do VR experiences influence telepresence?
- To what extent does message framing influence telepresence?
- does telepresence influence PEB?
- does perceived risk (severity, susceptibility) mediate this effect?
- does emotions mediate this effect?
- does psychological distance moderate this effect?

2 Theoretical Framework

2.1 Environmental Concern and Pro-Environmental Behaviours

Environmental concern refers to behaviour aimed at preserving the ecosystem. It integrates the components cognitive, affective and conative. The **cognitive** dimension refers to all subjective knowledge relating to environmental issues. The **affective** dimension refers to emotional responses linked to perceived problems in the environment, refers to interest in the environment in relation to other areas of interest. The **conative** dimension refers to individual's active involvement in protecting the environment, perhaps defined as an intentional action on the part of an individual or a group, which aims to benefit the environment directly or indirectly and whose harmful effects are limited.

2.2 Effects of telepresence in Virtual Reality on adopting pro-environmental behaviours

In recent years, research into immersion in mediated experiences has increased considerably, mainly due to the emergence of VR (e.g. Li, Daugherty, and Biocca, 2001). Serious games have also seen exponential growth in many areas (e.g. education, leisure, health, training, sales). A number of studies have highlighted their highly immersive properties and their ability to promote telepresence (e.g. Bouvier, 2009; Draper, Kaber and Usher, 1998; Lee, 2004; Stanney and Salvendy, 1998). In addition, other research (e.g. Fauville *et al.*, 2021; Markowitz *et al.*, 2018; Queiroz *et al.*, 2022) has highlighted their learning abilitie. Some research has also looked at the effects of immersive technologies on reducing PD and increasing PEB (e.g. Ahn *et al.,* 2016; Blascovich and Bailenson, 2011; Breves and Heber, 2020). To our knowledge, no study has examined the effect of telepresence in a VR educational experience to justify the adoption of PEB. To fill this gap, this research aims to explore the role of telepresence as a determinant of PEB.

2.3 The Mediating Role of Emotions and Perceived Risk

Previous work has highlighted the effects of telepresence in virtual experiences on both positive and negative emotions (e.g. fear, worry, concern, satisfaction, perceived well-being, empathy) and behavioural intentions (e.g. commitment, word of mouth – e.g.

Chirico and Gaggioli, 2019; Meijers *et al.*, 2023; Oh *et al.*, 2021; Raza, Wasim and Ishaq, 2024; Schutte and Stilinović, 2017). While, others have highlighted the effects of telepresence on perceived risk (e.g. Ahn *et al.*, 2018; Pimentel and Kalyanaraman, 2024; Plechatá *et al.*, 2022). However, appeals to fear and risk in a global manner can sometimes be inappropriate and not have the desired effect, and at present there is no scientific consensus on how to communicate the consequences of climate change in a way that encourages adaptive behaviour. Based on the literature (e.g. Hunter and Röös, 2016; Meijers *et al.,* 2023; Spence *et al.*, 2011, 2012), we believe that exposure to a highly immersive experience will lead to stronger emotions and consequently an increased perception of risk. Thus, in line with previous studies, in this research, we explore how the emotions induced by telepresence and associated with exposure to virtual reality can increase the perception of risk to the environmental cause and increase the intentions to adopt more responsible behaviour. We propose to study perceived risk from a two-dimensional angle: severity and susceptibility.

2.4 The moderating role of psychological distance

In their work on the theory of levels of representation, Trope and Liberman (1998) indicate that PD determines the level of mental representation that individuals have of a concept, modifying their behaviour. Researchers identify four dimensions to PD: spatial, temporal, social and hypothetical. The **Spatial** dimension refers to geographical distance between the individual and the phenomenon. The **temporal** dimension concerns individuals' perception of a phenomenon in terms of time. The **social** dimension involves the degree of personal proximity or connection with the phenomenon. The **hypothetical** dimension refers to people's perception that an event is real or tangible, certain or uncertain, as opposed to imaginary.

The greater the spatial, temporal, social and/or hypothetical distance of a phenomenon, the more psychologically distant it appears. Numerous studies suggest that the closer an environmental cause seems, the more concrete the visualisation of the risks and issues involved, the stronger and more negative the emotions felt, the greater the motivation to act, the sense of emergency, commitment and behavioural intentions. Conversely, the more distant a phenomenon seems, the more commitment decreases (e.g. Brügger *et al.*, 2015; Jones, Hine and Marks, 2017; Rickard, Yang and Schuldt, 2016; Scannell and Gifford, 2013; Spence *et al.*, 2011, 2012; Zhang *et al.*, 2014). Thus, psychologically distant events would be considered less important, less severe. To this end, recent work (e.g. Ahn *et al.*, 2016; Blascovich and Bailenson, 2011; Breves and Heber, 2020; Raja and Carrico, 2021) has mobilised this theory and has shown that immersive technologies, have the potential to reduce PD and increase PEB. However, the results on the subject are still mixed. Thus, we propose to study psychological distance from 2 angles. Firstly, by manipulating the framing (proximal vs. distal) of the experiment by modifying the scenario experienced by the participants. Secondly, by measuring psychological distance before starting the experiment and after the experiment in order to determine whether this evolves and moderates the overall effect of the model.

3 Methodological Framework

3.1 Main Concepts and Research Model

Our review of the literature and our initial empirical studies provide a framework for our thinking:

H1: (a) Experiences in VR (vs. 2D) have a positive effect on telepresence,
H1: (b) Close (vs. far) message framing has a positive effect on telepresence,
H2: (a) Telepresence influences int. and PEB,
H2: This relationship is mediated by emotions (b), and perceived risk (c),
H3: Close psychological distance attenuates this effects.

3.2 Proposed Methodologies

We will adopt a longitudinal quantitative methodology in the form of experiments. Two groups of students will be surveyed: telepresence (2D vs. VR) and message framing (near vs. far) will be manipulated so that one group will participate in a highly immersive experience and a second in the same experience in a less immersive form. A 3rd control group will be introduced and will not take part in any experiment. Individuals will be questioned via a questionnaire test before and just after exposure[1] about their emotions, their perception of risk, their intentions to adopt a PEB, their PEB (self-declared and observed), their PD regarding to the environment and their degree of telepresence. Finally, socio-demographic information will be collected, as well as information about their habits towards technology and their contact with nature (past and present). The data will then be analysed using software. Our analysis will enable us to test causal relationships and ensure the validity of the proposed hypotheses.

3.3 Progress to Date and Initial Proposals

So far, two exploratory studies on the effects of climate change have been carried out: '*The Virtual Arctic Expedition*' by @*VirtualGamesPark* and '*Pollinator Park*' by the European Commission. Semi-structured interviews were conducted (Study n°1 N = 52, i.e.16 groups, study n°2 N = 16). Including playing time and questions, the interviews lasted approximately 1 hour and were then analysed manually by theme and using a software. The results obtained demonstrate that VR experiences could improve the affective and cognitive dimensions of environmental engagement in particular by influencing emotions, reducing psychological distance or increasing perceived risk.

3.4 Main Areas for Consideration

However, a number of elements relating to the theoretical, conceptual and methodological framework are still under consideration. The doctoriales proposed by

[1] We also plan to continue the survey over time.

the Laval Virtual would enable me to clarify certain aspects of my research design, to obtain a complementary perspective to that of my supervisors on my work, to exchange ideas with experienced professionals and to meet doctoral students from a variety of backgrounds.

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MATCH: a mixed-reality cognitive assistance technology to support independence at home for older adults with neurocognitive disorders

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Abstract

We present MATCH, a mixed-reality assistive technology for cognition to support independence at home of older adults with neurocognitive disorders. We designed, developed and evaluated MATCH following a human-centered design approach. This paper presents an overview of the methodology used for this project, the results and a discussion.

1 Introduction

Cognitive decline might impact independence at home of older adults. Maintaining independence at home of older adults is one of the solutions proposed to leverage the worldwide societal and economic problem of aging (Rudnicka et al., 2020). Executive functions (ability to formulate a goal, plan the task to achieve this goal, carry out the task and verify attainment of the goal) are cognitive functions that play an important role in the ability of the individual to live at home independently (Lezak, 1982). Assistive technologies for cognition can be one of the solutions to maintain functional independence (Adelman et al., 2014). Boger et al. (2018) have developed the principles of zero-effort technologies (ZET), which aims to encourage the development of technologies for which use do not require cognitive effort. The ZET principles could theoretically increase the adoption rate of assistive technologies, which remains low (Van Der Roest et al., 2024). Pure mixed reality (PMR) could, from a theoretical point of view, support the ZET principles. PMR is an "independent dimension falling between augmented reality and augmented virtuality and characterized by the total blend of virtual holograms with the real world" (Flavián et al., 2019, p. 549). However, to the best of our knowledge, no assistive technologies for cognition using PMR supporting executive dysfunctions are developed using ZET principles (Spalla et al., 2024c).

2 Related work

Assistive technologies for cognition have the potential to support individuals with executive dysfunctions (Cook and Polgar, 2015). However, it is suggested that these technologies should minimize cognitive load (Spalla et al., 2024c). From our scoping review on the topic (Spalla et al., 2024c), only one PMR assistive technology for cognition supports executive dysfunctions (Wolf et al., 2019), but only partially, without being context aware and designed following the ZET principles. Only a few studies focus on PMR assistive technologies to support independence at home of older adults without and with neurocognitive disorders (Blattgerste et al., 2019). Nevertheless, it is suggested that PMR has the potential to support people with disabilities and that is likely to become more widely available when prices become more affordable (Blattgerste et al., 2019). It is suggested to design simple and intuitive user interface (Berrett et al., 2022; Rohrbach et al., 2019). Studies suggest the efficiency, acceptability (Wolf et al., 2019) and usability (Rohrbach et al., 2019) of PMR, without requiring a high cognitive load (Wolf et al., 2019). However, the definition of the types of assistance that may be possible using PMR requires more research (Wolf et al., 2019; Rohrbach et al., 2019).

3 Thesis statement

PMR represents interesting assistive technologies for cognition to support independence at home. The development of dedicated user interfaces particularly merits attention, as does refining the types of technology-provided assistance. PMR may be of interest in the development of ZET for older people with neurocognitive disorders, but currently, no PMR assistive technologies for cognition are developed following these principles. Hence, the objectives of this PhD project are to: 1) design and develop MATCH (Mixed reAliTy Cognitive ortHosis), a ZET for cognition based on PMR to manage executive dysfunctions; 2) evaluate the utility, usability and cognitive load of MATCH. The utility and usability are evaluated, as they are the first aspects to evaluate when designing a new system (Nielsen, 2010). The research questions we aim to answer from these objectives are: 1) is MATCH useful in supporting independence of older adults with neurocognitive disorders?; 2) is MATCH usable?; 3) is the cognitive load required to use MATCH considered acceptable by users? I successfully defended my PhD on February 14, 2025. I hope to submit the final version of my thesis by May 2025.

4 Methodology

ZET suggest answering real-world needs (Boger et al., 2018). Therefore, we followed a human-centered design approach. We first created *personas* (specific fictitious representations of target users (Pruitt and Adlin, 2006)), based on a quantitative analysis of assistance provided to older adults. We conducted three brainstorming sessions with 10 healthcare professionals and assistive technology development professionals, which helped us to define realistic scenarios that could guide the design of MATCH. We then designed and developed the prototype of MATCH, using the PMR headset Microsoft HoloLens 2. The design builds upon the results of the *personas*, the brainstorming sessions and human-computer interaction guidelines to design technologies for older adults and for PMR. We used an iterative approach, and we concluded each iteration with an expert review or a user study. The last evaluation we conducted focused on the perception of the utility, the usability and the cognitive load of MATCH. This evaluation followed a usability testing approach (Lallemand and Gronier, 2015). The same protocol was administered to each participant and in the same controlled environment. First, the Microsoft HoloLens was calibrated to their eyes. Second, they followed a tutorial to familiarize themselves with MATCH. Third, they were asked to perform an activity with MATCH, without knowing beforehand which activity it was. The activity consisted of cleaning a table. Finally, they were asked to fill in the CSUQ questionnaire (concerning utility and usability (Lewis, 1995)), the AttrakDiff questionnaire (concerning usability (Hassenzahl et al., 2003)) and the NASA-TLX questionnaire (concerning cognitive load (Hart and Staveland, 1988)) for quantitative analysis. Sessions were audio and video recorded for qualitative analysis. Twelve older adults without and with neurocognitive disorders participated in the study.

5 Results

We created three *personas* to support the design of assistive technologies for cognition from the perspective of executive dysfunctions to help us translate the needs of the people targeted when developing the technology (Spalla et al., 2024a). We have first identified the most appropriate types of assistance to provide to older adults depending on the executive dysfunctions. Each *persona* is illustrated with examples of assistance provided following a graded approach. We defined several design recommendations to support the design of assistive technologies for cognition for older adults on the dementia continuum, including stimulating the person to reason and act by themselves first and consider supporting the goal formulation and plan executive functions operations.

The brainstorming sessions allowed to conclude that transport, medication, cooking and home maintenance are the activities with the highest priority for support by the PMR. We selected home maintenance to guide the implementation of MATCH.

We designed MATCH with five packages (figure 1). The `Scenarios` package manages the activities to support. To do this, MATCH takes into account the context (using the `Inferences` package), with a graded cueing system developed for PMR, to provide the necessary and sufficient assistance to the user (Spalla et al., 2025). This graded cueing system is defined along two axes (figure 2—`Assistances` package). The first axis is a gradation from implicit to explicit (horizontal axis in figure 2). The second axis (vertical axis in figure 2) is a visual gradation, specific to PMR, to catch the user's attention in case they do not pay attention (Spalla et al., 2024b). The gradation between implicit to explicit can be adjusted according to the answers provided by the users. Activities and assistance can be fully customized. Each scenario is developed using a behavior tree (Colledanchise and Ögren, 2018) and each assistance is delivered using a graded approach. Gradation is managed by a second behavior tree, which is always the same, but adapts to the parameters provided, with a data structure containing the data shown in figure 2. We designed the software architecture to support additional assistance and activities. The `PathFinding` package is used for some assistance to compute paths in real time in the environment, and the `Utilities` package contains code used in various parts of MATCH.

The evaluation with older adults without and with neurocognitive disorders allowed us to conclude that MATCH could autonomously guide participants, providing necessary and sufficient graded assistance with a low cognitive load. It did not have any negative impact. Themes emerged related to the positive and negative aspects of utility, usability and social significance, including the possibility of exploring alternative methods of assistance based on the user's previous interactions with the system (Spalla et al., 2025).

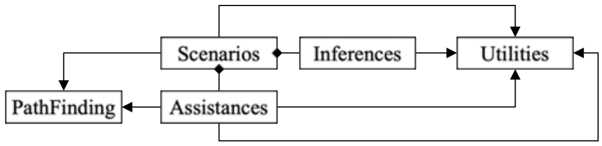

Figure 1: Overview of the architecture of MATCH (Spalla et al., 2025).

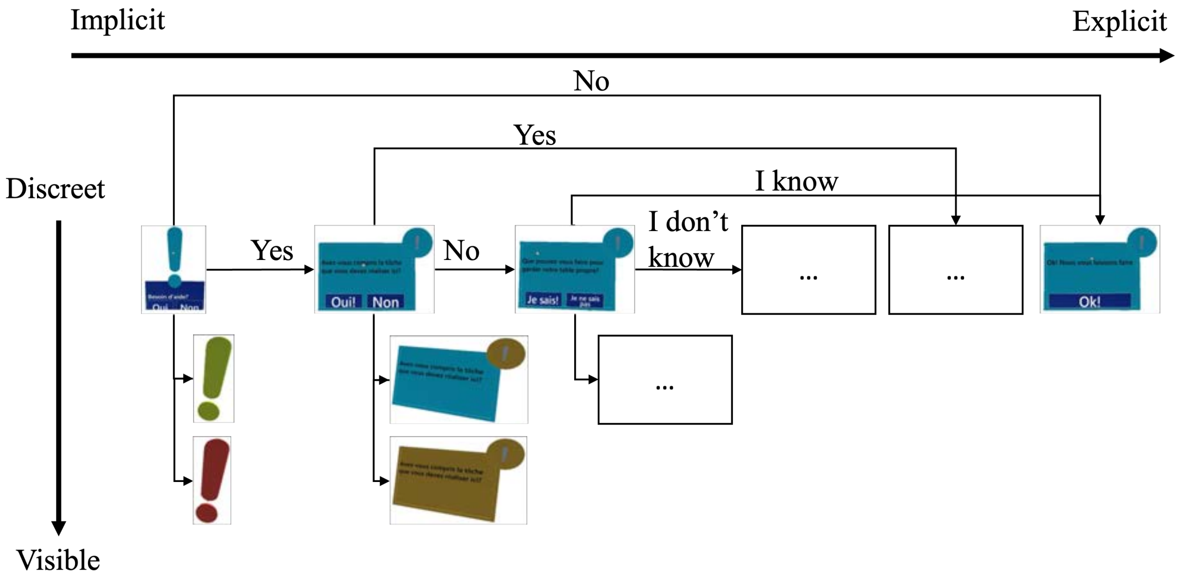

Figure 2: Design of the gradation system of MATCH (Spalla et al., 2025).

6 Discussion and conclusion

This project allowed us to understand in more detail which types of assistance an assistive technology should provide to support independence at home of older adults with neurocognitive disorders. It also allowed us to identify which activities a PMR assistive technology should support in priority. The design of MATCH led to a software architecture designed to deliver graded assistance in PMR. Our evaluation suggests that PMR can be useful and usable for older adults without and with neurocognitive disorders without requiring too much cognitive load. We have identified several potential lines of research, including the possibility of exploring other methods of assistance based on the user's past interactions with the system.

Acknowledgments

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The Use of Virtual Reality in Public Speaking Training: Design of a dedicated tool

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Abstract

Given their significance in many management contexts, public speaking skills are increasingly valued by organizations. Not always innate, these skills can fortunately be acquired through practice. However, due to their intrinsic social aspect, opportunities to refine these skills in real-life settings are scarce. Faced with such limitations, Virtual Reality emerges as a suitable and innovative solution. By simulating public speaking scenarios, it allows users to practice in front of an audience, albeit a virtual one. The added value of Virtual Reality public speaking tools is therefore clear, but the optimal training approach and environment design are not of a basic nature. In order to identify best practices, a dedicated Virtual Reality training system has been developed and will be presented in light of the scientific literature. The objective of the present research project is to leverage the system to investigate unanswered questions pertaining to the perception of virtual audiences, the evaluation of public speaking performance, and the effectiveness of such tools.

1 Introduction

Within organizations, Virtual Reality (VR) has emerged as a strategic tool with considerable potential in improving training programs (Ecorys, 2021). In many fields, the added value of VR for the acquisition of *hard skills* has been demonstrated, with positive training outcomes for both organizations and employees. More recently, *soft skills* training has also come into the spotlight. These skills, such as public speaking, are particularly sought after by companies due to their prevalence in management contexts. This has led to the emergence of dedicated VR tools, which constitute innovative solutions for public speaking training that address the limitations of traditional approaches.

However, best practices for designing such VR environments have yet to be determined. In fact, research on the effectiveness of public speaking tools is scarce in the existing literature. Further studies are needed to explore how the characteristics of virtual environments influence training outcomes in order to develop optimal solutions. To fill the identified gaps, a dedicated VR system has been developed. This system displays a realistic and responsive virtual audience that adopts specific attitudes towards the speaker, simulating a range of public speaking situations. The user's speaking performance is assessed using objective parameters, and personal feedback is provided. The aim of this system is therefore twofold: to provide individuals, especially students, with an accessible training solution while contributing to research in this field.

2 Theoretical Background

2.1 Virtual audiences perception

The audience's attitude can be stressful for speakers, therefore playing a crucial role as it subsequently affects performance. However, rehearsing in front of a real audience is impractical, which justifies the use of VR to get used to public speaking. The presence of a virtual audience is indeed beneficial for training (Chollet and Stefan, 2017). However, its design must be carefully considered, as audience characteristics shape user perception and influence the training approach. This highlights the need for careful audience design to preserve training effectiveness.

To understand this effect, perceptive studies have been conducted, either using screen-based or VR simulations, highlighting the impact of virtual agents' appearance and behavior on the speaker. Users can indeed detect changes in attitude and identify audience styles that reflect the interest, enthusiasm, and personality of the virtual agents (Kang et al., 2016). Agents' nonverbal behavior can also be associated with different levels of valence and arousal, with certain combinations of gaze, head movements, gestures, and postures being perceived as more positive than others (Chollet and Stefan, 2017; Etienne et al., 2023). In Glémarec et al. (2021) and Kang et al. (2016), these variations in valence and arousal were used to create audience types, such as critical, bored, enthusiastic, neutral, and indifferent audiences. A wide range of factors influence audience modeling, as highlighted by the systematic review in Etienne et al. (2024), including characteristics such as the agent's appearance, behavior, and emotional expressiveness, as well as user-specific factors like age and cultural background. Among these, the agent's gender has been identified as a significant factor in shaping user perception, further expanding the scope of audience modeling (Armando et al., 2022).

2.2 Public speaking performance assessment

Objective parameters for predicting performance have been identified in the literature. These include the speaker's gaze, behavior, facial expression, speech content, voice signals, pause timing and disfluencies (Wörtwein et al., 2015). Ideally, both verbal and nonverbal signals should be considered, as multimodal cues appear to be better predictors of performance (Chen et al., 2015; Chollet and Stefan, 2017). The evaluation of public speaking performance remains however a complex concept and as such, it is challenging, if not impossible, to accurately rate it. Moreover, it is often a matter of context and personal judgment, which even more increases the number of relevant parameters and the task intricacy.

3 System Presentation

The VR training system presented in this paper consists of a series of rooms, namely *the Boardroom, the Auditorium, the Classroom, the Courtroom, the Office* and *the Meeting Room*, each meticulously designed to replicate traditional settings for common public speaking scenarios. This provides users with an immersive and realistic learning environment, tailored to their needs, where they can practice in front of a virtual audience.

3.1 Audience design

A range of audience types were designed, incorporating variations in age, appearance, and behavior to align with the chosen training room. These audiences comprise photorealistic virtual agents representing diverse ethnicities and genders. The absence of uncanny effects in the resulting virtual audiences, as observed in Etienne et al. (2023), justifies the preference for photorealistic agents.

The library of nonverbal behavior developed by Etienne et al. (2023) has been used in the present system. Their combinations of head movements, gestures and body postures allow to design various audience types, reflecting differing levels of presentation appreciation, aiming to challenge the speaker effectively. Furthermore, contextual behaviors were integrated into the different rooms, leading to virtual agents that, for instance, might ask questions in the *Classroom* environment or listen attentively while taking notes on their computer in the *Meeting Room*.

3.2 Performance feedback

Given the complexity of public speaking performance assessment, the present system aims to identify key indicators that should be considered to provide speakers with representative feedback and areas for improvement. To this end, a dashboard of performance indicators has been designed to provide feedback to users through an associated website. Specifically, the audio is recorded, transcribed on the website, and processed automatically to determine the fundamental frequency and voice intensity over time. Furthermore, the user's hands, head and gaze are tracked and incorporated into the feedback. It is important to note that the performance indicators, which are only computed upon user consent, are based on both verbal and nonverbal behavioral cues.

3.3 Methodology

The library of nonverbal behaviors integrated into the present system has been first validated on single agents (Etienne et al., 2023). Given the nature of public speaking tasks, an extension of this perceptual study is being considered, focusing on whole audiences to assess whether the library remains valid while maintaining a high level of realism.

To facilitate interactions, the system also aims to implement automatic reactions from the virtual audience based on the speaker's performance. Achieving this requires the development of advanced audience and performance evaluation models. The appropriate behaviors will be selected from the validated animation library according to the intended perceptual effects, incorporating context-specific indicators. However, the current set of performance indicators integrated into the system remains limited. This research therefore aims to expand and validate the proposed dashboard to enhance the quality of feedback provided to users.

The effectiveness of this solution will also be examined, with comparisons made to other training approaches to assess the added value of VR tools. These findings will be analyzed alongside measures of presence (Bouchard and Robillard, 2019) and acceptance of the system.

4 Contributions

Public speaking training is an emerging research area, at the intersection of psychology, speech therapy, educational science, and computational science. Results are therefore scattered across these different fields, with links between them that need to be explored in order to develop effective and comprehensive training applications. The development of the present VR system will advance research in this domain and contribute at multiple levels. First, it will provide deeper insights into the design of virtual audiences of varying sizes and characteristics, facilitating the creation of effective VR public speaking environments. Additionally, it will contribute to the identification of relevant and interpretable performance indicators, facilitating the creation of constructive feedback for users and supporting their improvement. Finally, the effectiveness of the resulting tool will be assessed. The system has already been used in collaborative experiments with field experts, particularly in training future lawyers and secondary school teachers. These studies have demonstrated high levels of acceptance and sense of presence, providing promising indications of the system's effectiveness.

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Understanding the Influence of Visual Metaphors on Cognitive and Transdisciplinary Collaborative Conceptual Co-Design Activities

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Abstract

This research, at the beginning of a doctoral thesis, focuses on the critical yet ambiguous conceptual design (CD) phase in systems engineering. While Model-Based Systems Engineering (MBSE) is increasingly used, its reliance on 2D symbolic notations like SysML hinders acceptance and collaboration among multidisciplinary stakeholders. This study explores how 2D/3D visualizations combined with symbolic/iconic and stereoscopic/monoscopic devices influence cognitive and collaborative activities during transdisciplinary co-design. By addressing challenges of engagement and comprehension across experts and non-experts, the research aims to provide insights into designing more inclusive and effective external representations in MBSE.

1 Introduction

Hyperconnectivity and technological advances have revolutionized Systems Engineering (SE) (Madni et al., 2023), driving a shift from document-centric to model-based systems engineering approach (MBSE) with a strong focus on the critical conceptual design (CD) phase.

While languages like SysML are used to model abstract system aspects, their 2D symbolic visual syntax poses challenges. These limitations hinder their acceptance and reduce collaboration with non-experts in the notation (Pinquié et al., 2023). Indeed, some rely on 2D or 3D design artifacts they are accustomed to, causing a lack of integration between teams.

Previous studies have sought to address these challenges by introducing 3D immersive virtual reality for collaborative model-centric reviews on case studies, such as that of a telescope (Romero et al., 2021). Pinquié et al. (2023) argued for the added value of human-centric 3D visuals compared to 2D diagrams, but only at the level of experimental functional demonstrators, not within ecological or real-world settings. Moreover, engineers face difficulties in specifying virtual environments for CD due to the lack of research-based guidelines and ergonomic criteria.

The conclusive concern of Pinquié et al. (2023)'s study highlights the foundational common thread of this thesis: **How do visual metaphors influence the cognitive and collaborative activities of stakeholders involved in transdisciplinary co-design within the conceptual design phase?**

This preliminary literature review emphasizes the role of cognitive processes in collaborative conceptual design with models, examines challenges in using models, visual metaphors, and virtual reality, and aims to identify research gaps and perspectives for the thesis.

2 Conceptual Collaborative Design

CD phase is the earliest and most ambiguous phase of the design process (Hay et al., 2017). Many life cycle and product development models focus on this phase, emphasizing activities such as defining the problem space, exploring solution options, identifying business or mission requirements and stakeholder needs, and incorporating feedback from current and potential stakeholders to estimate costs and assess life cycle performance (INCOSE, 2023).

CD is inherently a multidisciplinary (engineering, architect, marketing, quality, etc.) process that requires better collaboration and communication among all stakeholders through interconnected artifacts (Shoshany-Tavory et al., 2023). Although models can facilitate collaboration by serving as a single source of truth, MBSE is still in its early stages, and gaps in methodology and tool maturity persist (Madni and Sievers, 2018). The challenge partly lies in the fact that models represent large amounts of information tailored to specific expert views, which facilitates collaboration among experts but excludes other stakeholders (e.g. quality assurance, operations, procurement, marketing). This exclusion contradicts the integrated nature of systems engineering.

Drawing on a background in human factors and ergonomics, as well as testimonies from researchers and practitioners, we will explore the idiosyncratic nature of collaborative conceptual design activities. It adopts an ergonomics-based approach to collaborative activity analysis, focusing on relevant topics such as cognitive synchronization among participants during synchronous co-located collaboration, multidisciplinary learning, and particularly the external representations mobilized in model-based conceptual design (MBCD).

Collaborative design has long been investigated in engineering. Although insights from detailed design exist, they can't be directly applied in the conceptual phase due to its broader scope and the need for multiple stakeholders' input. Indeed, to our knowledge, few studies have explicitly addressed literally collaborative design within the MBSE framework during the CD phase. Most are likely limited to experimental studies or proofs of concept. Paying specific attention to the unique characteristics of external representations mobilized in MBCD, understood as visual metaphors, and their cognitive impact, is a novel approach.

3 Model-Based Conceptual Design

MBSE represents a paradigm shift in SE, transitioning from a traditional document-based approach to a system model or combination of models. INCOSE defines MBSE as "*the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the [concept stage] and continuing throughout development and later life cycle [stages]*" (INCOSE, 2023) (p.219).

Although MBSE spans the entire life cycle of system development, the conceptual design phase remains an area where knowledge is still evolving (Madni et al., 2023). MBCD is defined as the application of MBSE during these early conceptual stages (Morris et al., 2016). The activities performed in this phase, known as systems architecting, result in an architecture—a holistic view of the entire system (Madni et al., 2023). Their importance cannot be overstated, as decisions made during the concept stage critically shape the possibilities for all subsequent stages, becoming increasingly difficult to alter (INCOSE, 2023).

SysML is the most established language for architects in MBCD, extensively supporting the specification of needs, the definition of operational scenarios, and the description of a system's functions, structure, and behavior through diagrammatic notations. However, despite offering both symbolic and iconic forms, these graphical notations often limit team understanding, are perceived as overly esoteric by some stakeholders, and lack acceptance (Pinquié et al., 2023).

4 Visual Notations of MBCD

The lack of acceptance of visual representations, which is problematic for both engineers and non-experts (business, marketing, operations, quality), can be attributed to a lack of scientific foundations for their proper design (Moody, 2009).

Some researchers (Pinquié et al., 2023; Romero et al., 2021) have argued for partially replacing 2D diagrams with 3D stereoscopic visuals to enhance multidisciplinary co-design activities and the use of immersive virtual reality. Pinquié et al. (2023) applied Moody (2009)'s principles for designing effective visual notations to compare 2D and 3D representations, highlighting their critical role. These efforts align with INCOSE's prediction that the future of SE will be immersive (INCOSE, 2021). As Waguespack (2010) observed, a model (or set of models) is a conceptual metaphor, and the challenge is to design representations that, despite their abstraction, ensure stakeholder satisfaction. However, Pinquié et al. (2023) noted that many modeling notations lack sound theoretical underpinnings and are derived from syntactically ill-defined visual modeling notations.

Interest in model visualization has led to the integration of immersive tools to enhance collaboration. Visual metaphors, like cities and islands in software architecture, are used in UML diagrams, but their impact on activity and cognition (Romero et al., 2021) requires further exploration, particularly in multidisciplinary computer-supported collaborative work.

5 Computer Supported Collaborative Work

As Masclet (2023) noted, the design community has been transformed by computing technology, the internet, and increased labor division, making computer-assisted design and multidisciplinary collaboration essential.

Integrating virtual reality into MBCD enhances system understanding, allows exploration of large datasets, and promotes multidisciplinary collaboration (Romero et al., 2021).

Additionally, system data presented as external representations serve as intermediate and/or boundary objects, acting as indispensable communication tools facilitating stakeholder collaboration. De Vries and Masclet (2013) highlighted the necessity of considering both the cognitive and semiotic perspectives of representations.

6 Conclusion

Against this backdrop, we propose to explore the following research questions during the doctoral consortium:

1. What are the motives of reluctance among engineers to transition from 2D symbolic diagrams to 3D iconic visuals?

2. How does the human cognitive system process the specific visual metaphors mobilized during MBCD activities?

3. How can we guide the development of vehicular visual metaphors that enable the participation and engagement of a multidisciplinary team during MBCD activities?

4. What approaches can be used to develop metrics for assessing the quality of group collaboration during MBCD activities?

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Optimizing social interactions in VR

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Abstract

Technological developments have made Virtual Reality (VR) technologies accessible, and have democratized its use for industrial, cultural or entertainment purposes. VR can be seen as a unique medium: while being immersed together in a virtual environment (VE), people can feel the presence of each other as if they were in the same physical space even if they are far apart in reality. This phenomenon is known as co-presence. The VR medium introduces specific factors influencing on the dynamics of the social interaction. This PhD project aims at understanding that dynamics through the study of co-presence.

1 Introduction

Social interactions can be defined as a reciprocal influence between individuals (Stébé, 2007), influenced by the social and physical environment (Newcomb, 1953). Social interactions are essential for human beings. Social identity emerges from the interaction between the individual and their social environment (Luckmann and Berger, 1989). The onset and development of one's social identity are linked to social representations, which are defined as conceptual constructs stabilizing one's relationship with their environment. They guide one's understanding of the world and helps to adapt to it with the considered right actions and practices (Rouquette and Rateau, 1998). The understanding of one's physical environment rises from one's interactions with this environment. Based on past experiences, the brain "predicts" possible events and the actions to be taken to reduce the probability of "surprising" events (Friston, 2010). Social interactions are as well largely determined by this prediction system. In VR, it is possible to recreate realistic social situations and if they correspond to the brain's predictions, participants will react in a realistic way (their behaviors and emotions will be similar to the ones they would experience in a real situation) (Slater, 2009; Hortensius et al., 2018).

Technological advancements allow for multi-user VR applications, where each user is represented by an avatar, enabling social interactions within the VR. For reciprocal influence in social interaction, it is necessary for users to feel co-presence (Schroeder, 2006; Zhao, 2003), through avatars.

Therefore, this PhD project is guided by three general research questions: Which parameters are essential for communication and social interactions between individuals in reality? Which of these parameters can be reproduced in VR? Which parameters are essential for communication and social interaction in VR?

2 Co-presence in VR: experiments

To better understand the dynamics of social interaction in VR, understanding co-presence is necessary. To achieve this, we have created a collaborative VR application (Fig. 1) with a shared goal. Two participants viewed and reproduced a virtual pattern, aiming to gain points by correctly replicating the patterns. The participants were physically located in separate rooms. In the VE, each of the participants was represented by a full-body avatars, sitting in front of each other, separated by a virtual glass. This application allowed us to measure social behavior through hand movements and task performance (score and completion time) as objective measures, in addition to subjective questionnaires measuring, e.g., social presence (Harms and Biocca, 2004), motion sickness (Keshavarz and Hecht, 2011), emotions (Russell et al., 1989), mental state sensibility (Baron-Cohen et al., 2001) and embodiment (Gonzalez-Franco and Peck, 2018).

Figure 1: First-person view during the VR collaborative task.

2.1 Impact of Social Representation on Co-presence in a VR Collaborative Task

The objective of our first experiment was to objectively measure co-presence. To achieve this, we established an experiment designed to induce variations in co-presence by changing the social representation of the virtual partner, using the VR application described above. Abric's study (Abric, 1989) indicates that a change in behavior is observed when the social identity of a partner is changed (e.g., between human and machine). In one condition, participants were told collaborating with a student situated in another university (human condition), and in the other condition they were told they were interacting with an AI controlling the avatar sitting in front of them (AI condition). In reality, participants collaborated with each other in both conditions.

The main results indicate significant differences in co-presence levels between the AI condition and the human condition. However, no significant differences were observed in terms of task performance. Though, no other significant differences were found in the questionnaires. We suggest that the social representation of AI explains these results,

Figure 2: The avatar appearance tested in the experiment, from left to right the meshed avatar to point-cloud avatars with decreasing number of points. Equivalence for Male avatar were enable.

leading to differences in co-presence and not in performance (score and completion time). This aligns with the studies of Abric (Abric, 1989) and Poinsot (Poinsot et al., 2022). Additionally, a correlation test demonstrated a correlation between co-presence and elements of social interaction, and not with task performance, confirming that co-presence is subjective and that performance cannot be used to objectively measure co-presence.

2.2 Metaphor for Representing Human Movements: Does the Avatar Appearance Really Matter?

Based on this first experiment, we studied how co-presence varies as a function of how participants' movements are represented (avatar appearance) during the same collaborative task. For this new experiment, the VR device was different (Quest Pro instead of Quest 2), as well as the relationship between participants (known virtual partner instead of unknown or AI). We compared point-cloud avatars with meshed avatars, varying the number of points, resulting in four different avatar versions (Fig. 2). Each avatar was animated and used the same motion capture system.

Initial results show differences in terms of embodiment, especially in External Appearance (Gonzalez-Franco and Peck, 2018), and no differences in social presence, emotions and performance.

3 Towards a First Attempt to Describe the Dynamics of Social Interaction in VR

Our two studies help us to better understand co-presence: a subjective feeling linked to social interaction. By defining co-presence as "being there together" in the VE, we suggest that multiple factors contribute to shape this perception.

First, as presented in the introduction, each individual has their own "internal model" (Friston, 2010): identity, social representations, predictions and *qualia*. Each individual has a unique experience of the world and therefore, their own beliefs about it. Secondly, the specificity of VR introduces various factors that can impact the experience: **Hardware** (e.g., beliefs about it or prior experience with it, ergonomics, or brand); **VE**

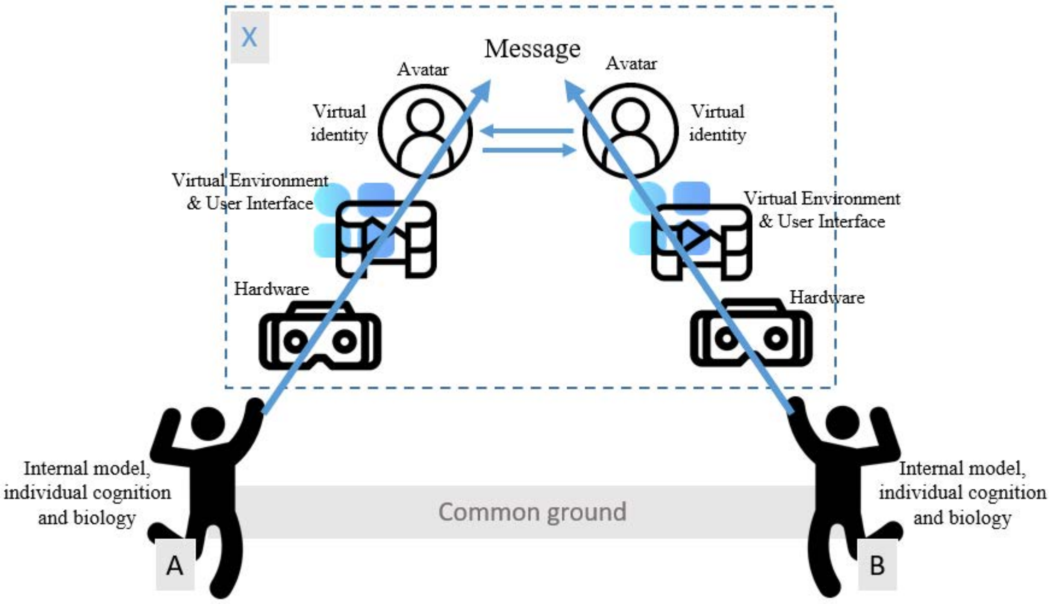

Figure 3: Dynamics of social interactions in the VR proposed model, inspired by Newcomb's ABX model (Newcomb, 1953).

and User Interface (e.g., complexity, colors, shape); **Virtual identity** (e.g., avatar appearance, movement fidelity, embodiment, Proteus effect (Yee and Bailenson, 2007)). Each factor has a reciprocal influence with individuals: the internal model influences the perception of each factor, and each factor can influence the user (e.g., Proteus effect, cybersickness, presence, etc.). Finally, social interaction can be modelled by considering the relationship between interlocutors, the physical and social environment and the common ground (Tomasello, 2010).

Hence, we propose a model representing the dynamics of social interaction in VR, following up on Newcomb's ABX model (Newcomb, 1953) (Fig. 3). In VR, social interactions do not occur directly between the two actors (A and B), but through their avatars. We therefore propose a sequence of factors impacting this interaction, accounting for the user's experience of VR. The resulting message is constrained and influenced by the entire preceding sequence; its form and content are impacted. If one aspect (A,B or X) changes, the entire dynamics changes as well.

4 Conclusion and perspectives

The feeling of co-presence results from a set of influencing factors specific to the VR experience and personal experience, implemented in a dynamics of social interaction mediated by VR technology. Optimizing social interactions in VR requires an understanding of whether there are different levels of impact from these factors. We can suppose that the avatar plays an important role: social interaction is effective through it, as well as the understanding of others: verbal and non-verbal communication.

A potential direction involves applying the Proteus effect (Yee and Bailenson, 2007) in reverse: using abstract avatars that allow users to project their own body perception onto a minimal, neutral digital body, thus reducing bias introduced by avatar appearance.

To conclude, this work aims at understanding better social interactions in VR. With a social psychology perspective and the study of co-presence in a collaborative task, we have proposed a model of the dynamics of social interaction in VR. The following questions can be addressed and will be studied: How to validate or upgrade this model? Can it be used as a reading grid for developers, or to analyze and help make the analysis of mediated social interactions more systematic?

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Leveraging Generative Artificial Intelligence for Mixed Reality Educational Activities

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Abstract

This article explores the potential of generative Artificial Intelligence (AI) to facilitate the creation of Mixed Reality (MR) educational activities. Through a prototype integrating three AI modules (AI Prompter, AI Chat, and AI Tutor), the system enhances the design process by generating multimodal content, proposing activities based on existing teaching material, and offering personalized and immersive experiences to learners. The prototype was evaluated during a preliminary study with a teacher. The results show promising interest in these tools, while highlighting technical limitations requiring future improvements.

1 Introduction

Mixed Reality (MR), which combines real and virtual elements, makes it easier to understand complex concepts that are difficult to grasp using traditional methods (Aksayır and Aksayır, 2017). However, its content creation remains inaccessible to most teachers because of the technical skills required. Authoring tools, incorporating visual editors and simplified interactions, offer a promising solution for enabling non-programmers to design educational content (Cypher, 2010). Despite this, these tools have their limitations, particularly when it comes to helping teachers find inspiration or create resources such as images or 3D objects (Ez-Zaouia et al., 2023a).

Generative AI opens up new possibilities by simplifying content creation through natural language prompts and providing interactive assistance to teachers (Chiu, 2023). This technology could complement current authoring tools and unleash teachers' creative potential in the design of immersive content. With this in mind, we have developed MIXAP-IA, a prototype derived from MIXAP, an open-source authoring tool dedicated to the creation of educational activities in MR (Ez-Zaouia et al., 2023b).

2 State of the Art

As AI technologies gain in popularity, assistive modules are being deployed in many applications to simplify processes such as content creation or communication. For example, assisted writing in Gmail and designs generated by Canva show how AI is being integrated into workflows to reduce complexity. In education, tools such as PATHWISE (Rahman et al., 2024), which uses social bots to personalize lessons, and AIIA (Sajja et al., 2024), which offers tailored learning experiences, are transforming teaching. However, few studies explore AI in the creation of educational activities in mixed reality, a field requiring a precise correspondence between physical and virtual elements.

3 System Description

The MIXAP-IA system offers an intuitive interface to simplify the creation and previewing of MR content, with two main modes: Canvas mode and ARView mode. Canvas mode lets users create activities by adding multimedia content (text, images, video, audio, 3D objects, etc.) to a marker, such as a book page or exercise sheet, which is displayed in augmented reality. The ARView mode lets users test activities by viewing augmentations in augmented reality when the camera detects the marker. The system architecture is based on three AI modules interconnected to a centralized knowledge base, as shown in Figure 1.

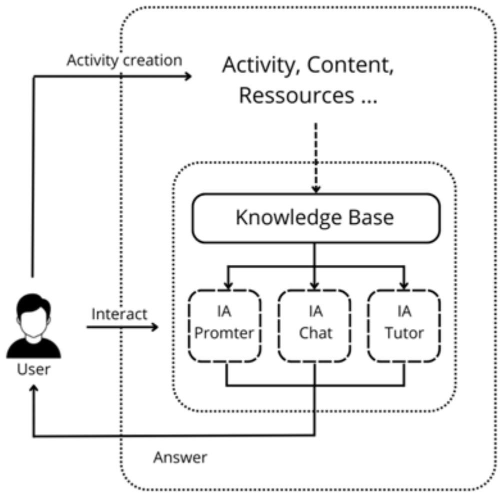

Figure 1: Architecture of AI modules.

The AI Prompter facilitates the creation of educational resources by generating adapted content, such as images or explanatory texts, from simple prompts (e.g., ‘lion’). These resources can be customized in the editor, as illustrated in Figure 2.

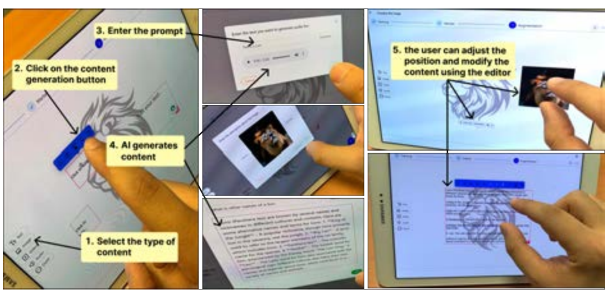

Figure 2: Using AI Prompter to create resources.

The AI Chat offers interactive assistance for creating and customizing MR activities, suggesting contextualized ideas and interactions, as shown in Figure 3.

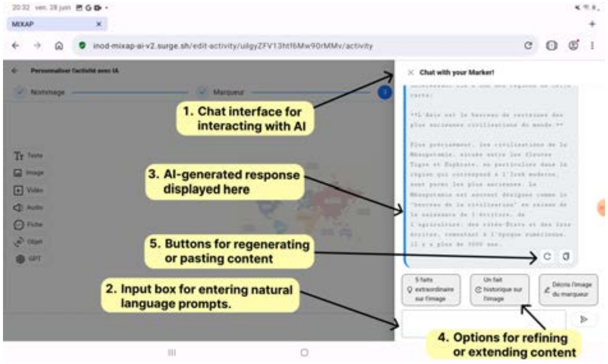

Figure 3: Using AI Chat to create activities.

The AI Tutor provides a personalized learning experience by offering adaptive guidance based on user interaction, as depicted in Figure 4.

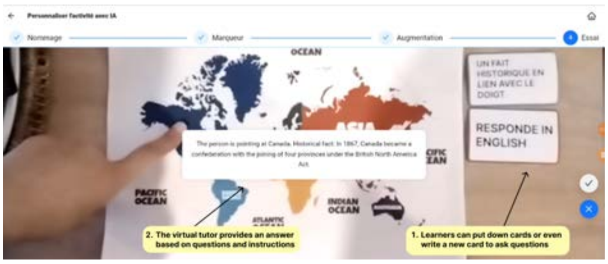

Figure 4: Using AI Tutor to create unique learning experiences.

4 Preliminary Study

A working prototype of MIXAP-IA was tested with an SVT teacher during a 75-minute session. The teacher designed and tested four educational activities incorporating AI modules, exploring subjects such as 3D printers, tectonic plates, and world geography. The results highlight the potential of AI modules to enrich educational activities, though manual adjustments and human validation remain necessary. The AI Tutor demonstrated effectiveness for immersive interactions, despite limitations such as low-light recognition and variable performance depending on the language used.

5 Conclusion

This article demonstrates that AI technologies, through modules like AI Prompter, AI Chat, and AI Tutor, can simplify the creation of multimodal content and offer personalized, immersive educational experiences in MR. However, limitations in content accuracy, environmental recognition, and language management suggest areas for future improvement. These modules hold great potential for transforming teaching practices and integrating mixed reality into educational settings.

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Systematic design and evaluation of immersive environments to support project in Living Lab mode

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Abstract

The application domains of Extended Reality and more specifically virtual reality (VR) have expanded rapidly, driven by the advancement and accessibility of immersive technologies. This growth has led to an increase in their use in both academic research and industry, showing concrete benefits in training, raising awareness in emergency situations, and providing remote collaborative spaces. In research, VR environments offer experimental advantages as well, notably due to precise control over variables, which offers better reproducibility. However, VR is not limited to its technological components. It is a multidisciplinary field that requires expertise in cognition, computer science, and engineering. Developing new VR applications presents a complex challenge, where integrating user feedback is crucial to mitigate potential negative effects. Despite the field's growth, few theoretical frameworks exist to guide the design process, and validation often relies on subjective self-reported questionnaires providing partial data on user experience (UX). This paper introduces part of our work to help formalize a design approach for VR systems, incorporating a comprehensive evaluation of UX through a combined methodology of subjective and objective indicators, including physiological measures. Conducted through a multidisciplinary collaboration, this research implements an action research approach to address the various levels and disciplines involved in VR system development.

1 Introduction and background

Extended reality (XR) is a multidisciplinary field that integrates specific technologies and enables the creation of diverse virtual environments. The benefits resulting from the use of XR are well-established and progressively recognized, notably in the industrial sector where it is used to support design review (Mastrolembo Ventura et al., 2020), collaboration (Wang et al., 2023) or training (Ulmer et al., 2022), to name but a few applications. However, despite the potential of the field, supported by increased technological development since the 2010s, mass adoption is still a long way off. In 2024, the main reasons identified behind this delay included poor user experience (UX) and lack of quality content (Perkins Coie, 2024).

XR hardware is radically changing the way users engage with virtual content, increasingly fine-tuning the real-virtual frontier and the adaptations required from users. As a result, designing new XR application can hardly be considered only from a technical point of view. It calls for approaches that account for users' cognition and the wide range of possible applications, which means that new methodological approaches are needed (Wohlgenannt et al., 2020).

In order to facilitate the understanding of the interdisciplinary nature of virtual experiences, the involvement of experts from various professional backgrounds, including psychologists, ergonomists, and cognitive experts is recommended, to enhance teams whose areas of expertise are more conventionally focused on the technical aspects of VR (Richir et al., 2015). While several design frameworks (Gong et al., 2021; Dietrich et al., 2021) or evolutions of traditional methodologies (Fleury and Chaniaud, 2023) have been proposed, there remains a lack of a comprehensive design approach dedicated to the design of new XR systems.

The field of XR operates within a dual-speed environment: while scientific research allows for a broad perspective, technological advances and evolving applications often outpace theoretical developments. Driven by societal and industrial demands, like the push for remote collaboration during the COVID-19 pandemic and the increasing digitization of industry toward Industry 4.0 and 5.0, number these innovations still require practical validation. Our research aims to bridge these temporal dynamics by fostering industrial partnerships to co-develop adapted and optimized immersive systems validated for specific application, leveraging a research-action approach grounded in real-world contexts.

This work is rooted in an interdisciplinary context articulating academic research and industry. At the ERPI research lab (Innovative Processes Research Team), XR technologies have been studied to support innovation processes, evolving from design visualization tools to platforms for co-creation, experimentation, and evaluation. Previous studies, such as Dupont et al. (2017), highlighted the complexities of evaluating UX in collaborative immersive environments and the limitations of relying solely on subjective measures. This led to an interdisciplinary collaboration with the 2LPN (Lorraine Laboratory of Psychology and Neuroscience) to better understand cognition and behavior in VR. Supported by a CIFRE contract with the SME TEA, this research also engages with industrial settings. The company, specializing in human behavior analysis in real-world environments, identified a need to help clients effectively adopt immersive technologies.

Hily et al. (2023) highlight that publications implementing VR show little evidence of iterative dynamics and interdisciplinary collaboration. UX evaluation methods are mostly reliant on post-experimentation questionnaires and interviews, meaning subjective data focusing on conscious phenomena. On the other hand, real-time physiological data collection remains a relatively weakly emerging trend within the set of studies considered. Additionally, opportunities for improvement stated in these studies include (1) choices concerning virtual content and technologies, (2) the protocol implemented to evaluate the system (e.g. UX indicators, tested population and the expertise involved), and (3) the overall implementation process (e.g. system integration, lack of process support, absence of cost management tool).

To contribute to this field, this research adopts a holistic perspective, addressing the interplay of various levels and disciplines within a VR system to facilitate its industrial adoption, emphasizing that VR encompasses more than just its enabling technologies. More precisely, we propose that the success of a new VR system hinges not only on technical development but also on the way the project is conducted and the effective integration of UX through a comprehensive evaluation combining diverse indicators.

2 Methodology

Our interdisciplinary research-action approach leverages a Living Lab framework to foster collaboration among academic and industrial stakeholders, promoting shared learning and iterative skill development. This approach has been implemented and refined through three case studies, shaping both operational and organizational aspects of our research (see Figure 1). On the *operational* level, the focus is on assessing the relevance of using sensors to evaluate the developed VR system, considering their usage, the validity of the results obtained, and their complementarity with other indicators. It also examines the feasibility of a broader deployment of sensor-based instrumentation and seeks to identify best practices to support this deployment. On the *organizational* level, the analysis aims to identify changes made to the design and evaluation process, determine relevant choices within specific contexts, and highlight potential improvements. It also seeks to recognize effective strategies for applying these processes more broadly and consistently across different contexts.

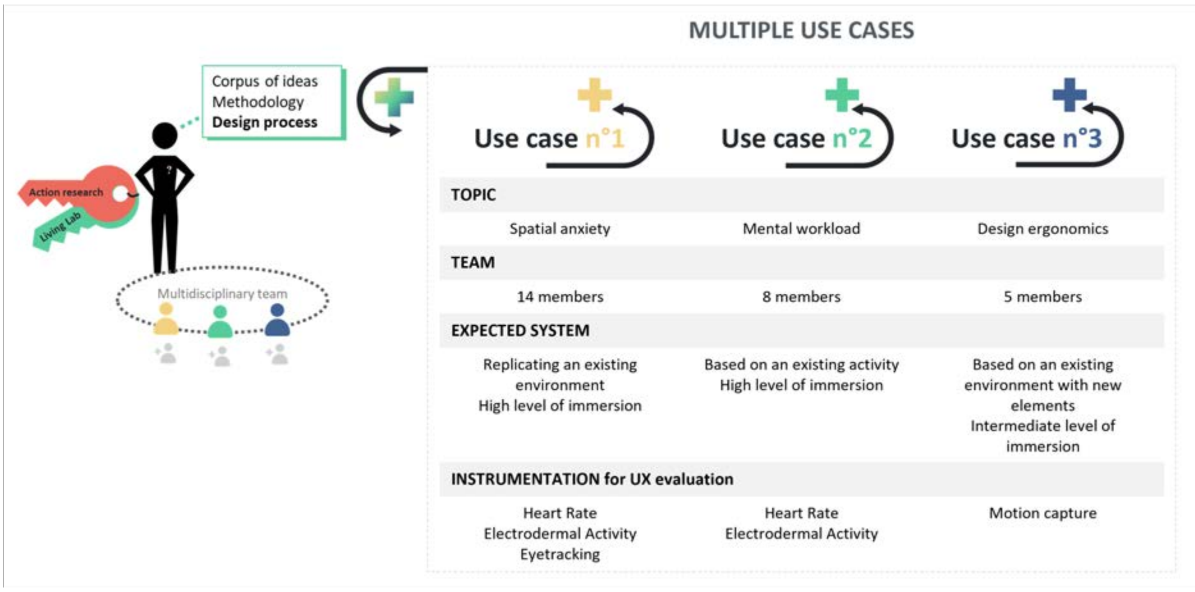

Figure 1: Representation of our research approach including 3 use cases

Three case studies were selected based on specific criteria: (1) technical and technological feasibility, (2) the ability to mobilize human resources, which requires an official framework and ideally secured funding, and (3) their capacity to meet the expectations of various stakeholders, ensuring engagement and investment from all parties involved. For more details, Hily et al. (2020) shared the first iteration of use case n°1.

Together, these three case studies form a coherent set for exploring the use of VR, enabling the application of our approach to develop and evaluate immersive systems using diverse UX indicators. Each study contributes unique elements, offering complementary insights and addressing variations in maturity, immersion level, and instrumentation.

3 Results

The execution and analysis of these case studies rely on a comprehensive dataset documenting our actions and their effects. As each study is unique, the selected indicators vary according to context and are not systematically applied across all cases. These indicators aim to evaluate both UX and the design process of VR systems, drawing from diverse data sources.

For UX evaluation, the collected data includes:

- Sensor data (physiological or biomechanical)
- Other objective data (e.g., performance indicators) or subjective data (e.g., self-reported questionnaire scores)
- Oral or written user feedback
- Photos and videos from experimental sessions
- Results analysis

For evaluating the design process, the collected data includes:

- Number, frequency, and type of meetings held by the multidisciplinary team
- Meeting minutes and reports from organized discussion groups
- Time invested in application development
- Project evolution and the development of intermediate design objects through iterations (e.g. protocols, virtual environments and interfaces, resources used, photos of experimental spaces)

In our research-action approach, the data collected at both the organizational and operational levels is not intended to define a single standardized process but rather to provide detailed documentation that lays the foundation for a more generalizable approach.

This work leads to the proposal of a structured methodology for VR system design and project management, based on the previously mentioned field data to address the following steps:

- Definition of system objectives
- Experimental protocol design, including the selection of indicators for combined evaluations integrating physiological and/or biomechanical measures
- Specification of the virtual environment and scenario
- Organization and execution of user-centered experiments
- Data analysis to validate system effectiveness
- Documentation and optimization of the process

This iterative process supports the progressive improvement of VR systems through mutual learning within the multidisciplinary team and user integration, ultimately achieving a system ready for final implementation.

4 Conclusion

Our findings highlight the importance of collaborative, interdisciplinary approaches in designing and evaluating VR systems, offering a toolset for managing innovative projects in this domain. The research not only advances user-centered design practices but also provides a strategic framework for managing VR design projects and their industrial adoption.

Our approach follows an iterative process aimed at the gradual improvement of the developed system, driven by the team's collective and mutual learning and the integration of user feedback. The process continues until the system reaches a level of satisfaction sufficient for its final implementation. The documented approach provides a structured framework that serves as both a project management tool and a methodological guide for design teams. It aims to support and formalize the different stages of designing and evaluating a virtual reality system, supporting a more effective and reproducible process. Further details on this work will be progressively published, in compliance with confidentiality agreements established with the research partners.

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AVATOUCH - Synchronous cooperation based on social intention for the manipulation of a virtual object in a collaborative virtual environment

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Abstract

The project focuses on cooperation for the manipulation of a virtual object by two individuals in remote immersive environments, without verbal communication or instruction, relying solely on gestures. Within the framework of the PEPR eNSEMBLE program, our aim is to strengthen this cooperation by drawing on theories from cognitive sciences, particularly the concept of intentionality in a social context. Indeed, during social interactions, individuals communicate their intentions and emotions through a variety of nonverbal cues. Among these, facial expressions, gazes, and gestures significantly contribute to the transmission of information that is essential for the success of social interactions. Moreover, inspired by the literature on social touch between humans and recent research on human-agent interaction with haptic feedback, we have worked at Heudiasyc on the sensation of being touched by an agent (ANR Socialtouch, ANR Match) in collaboration with ISIR (Catherine Pelachaud) in a virtual environment. These studies were conducted using virtual reality headsets, but to our knowledge, none have yet explored social touch between remote immersive rooms, involving life-sized user avatars. Therefore, the objective of this thesis project is to explore cooperation between remote users, represented by their virtual bodies (avatars) with multisensory feedback and intentional gestures, by adapting the paradigm of Quesque et al. (2013), with and without social touch, through a set-up consisting of two connected immersive rooms that are part of the CONTINUUM project.

1 Problem and objectives

The faithful representation of human gestural behavior through an avatar remains an important issue. Natural reactions observed in human-human or human-agent situations show that cooperation in an object manipulation task is determined by intentionality.

What we do not know today is how these reactions are:

- perceived in immersive, remote, large-scale environments (such as CAVE), where one's own real body and the other user's avatar (virtual body) can be seen,
- reinforced by social touch, which, according to our hypothesis, gives a greater sense of presence at a distance.

Our aim is therefore firstly to understand the mechanisms of remote cooperation between two humans who can only see each other's avatar, in order to manipulate a virtual object, based on social intentionality, and secondly to explore the impact of social touch for this remote cooperation, by equipping users with a haptic sleeve to reinforce social presence.

2 State of the art

In collaborative virtual environments (CVEs), metaverses or virtual worlds, the remote representation of users by avatars (virtual characters) reinforces the sense of presence. CVEs are based on the notion of sharing, this is why the acronyms DVE for Distributed Virtual Environment and SVE for Shared Virtual Environment coexist with CVE. The concept of presence is considered through two orthogonal components, namely Place Illusion and Plausibility Illusion (Slater, 2009). This categorization makes it possible to take into account temporal changes in the presence illusion, should it be broken during the experiment, for example. With this model, the initial notion of presence is contained in the location illusion, while the plausibility illusion is used to describe the coherence of the VE, the fidelity of the VE's scenario, its ability to correlate the user's actions with sensory feedback, and so on. As far as gestures are concerned, transitive gestures (i.e. significant gestures involving an object, subsequently referred to as object-directed actions) contribute to the success of social interactions. Indeed, work carried out at SCALab has shown that the execution of an object-gripping gesture is modulated by social intention, i.e. by the intention to include another person in the interaction with the object (Gigliotti et al., 2020). The modulating effect of social intention was observed through analysis of the kinematic characteristics of motor trajectories. Specifically, the trajectory of an object grasping gesture is generally characterized by a longer duration and higher amplitude when this grasping gesture involves another person (Quesque et al., 2013). Visual perception of these kinematic modifications induced by social intention plays a decisive role in social interactions and cooperative tasks (Lewkowicz et al., 2015). Kinematic modifications linked to social intention capture observers' attention (joint attention) and provide cues about the actor's intention enabling appropriate responses (Quesque et al., 2016). Surprisingly, it has recently been shown that social intention has little influence on object-directed motor actions when the partner in the task is a virtual agent (Gigliotti et al., 2024). However, this social interaction situation has never been studied in immersive reality, neither in a multi-platform context nor between avatars.

3 Research questions

It has been shown that the execution of gestures towards objects is modified by the social context. We spontaneously and implicitly perform wider and slower motor trajectories when actions performed towards objects involve another person (social intention) than when they involve no other person (personal intention). These slight motor variations are visually perceptible and contribute to the success of cooperative tasks (Lewkowicz et al., 2015). This specificity of motor actions performed in a social context has never been tested in immersive virtual reality involving distant locations and in the presence of avatars. Our hypothesis is that synchronous cooperation in a collaborative virtual environment between two users depends on the perception, authorized by the technical device, of the social intention in the avatar's gestures for each user. Moreover, the intensity of social interaction between two people depends on the contacts generated between them, notably through social touch. The planned study will therefore also test whether cooperation is enhanced by physical contact (haptic feedback via a sleeve) generated between the two people represented in a collaborative space by their avatars, by observing their gestures and social intention.

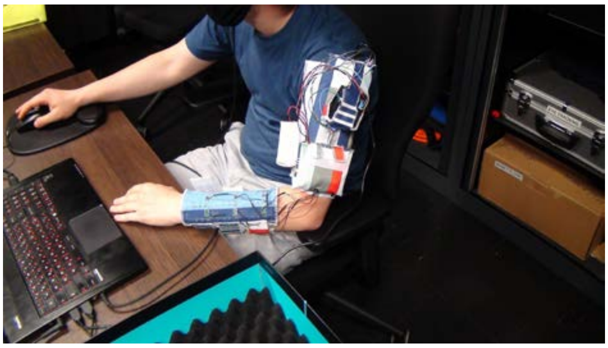

Figure 1: Haptic sleeve

4 Theoretical foundations

The modulating effect of social intention has been observed through analysis of the kinematic characteristics of motor trajectories. More specifically, the trajectory of a grasping gesture is usually characterized by a longer duration and higher amplitude when this grasping gesture involves another person (Quesque et al., 2013). Visual perception of these kinematic modifications induced by social intention plays a decisive role in social interactions and the success of cooperative tasks (Lewkowicz et al., 2015). Kinematic modifications linked to social intention capture the attention of observers and provide clues about the actor's intention enabling appropriate responses when it comes to cooperating (Quesque et al., 2013). This project thus focuses specifically on the concept of social intention between cooperating users who manipulate a virtual object, via their avatars, by reinforcing social presence through the contribution of the haptic modality (Richard et al., 2021).

5 Approach and methodology

The proposed approach combines the latest findings in neuroscience and interaction in virtual environments to:

- build a collaborative virtual environment using two very large heterogeneous immersive devices of the CAVE type,
- study cooperation via social intention based on virtual object manipulation gestures,
- integrate social touch by equipping each remote user with an intelligent haptic sleeve (Grandidier et al., 2021) to be touched by the other's avatar, and measure the impact of this feedback on cooperation between heterogeneous immersive devices in a shared virtual environment.

The proposed method thus aims to reproduce a real-world validated cooperation task based on the gestures of two face-to-face users, represented by their avatars, synchronously with and without social touch.

The thesis project started in January 2025 and will aim to:

- model and validate social interactions involving gestures directed towards objects in interactive time between humans and avatars in a virtual environment shared between the two remote immersive rooms (Compiègne and Lille),
- adapt a haptic interface enabling an avatar to be touched in an immersive room (adaptation of the Softly interface initiated by Grandidier (Grandidier et al., 2021)),
- design and implement an experimental methodology to test the effects of social intention and touch in motor gestures directed towards objects in an interaction.

The aim is to measure the effectiveness of cooperation through the performance of a subject executing a gesture responding to a social intention in front of an avatar, and that of the subject detecting the social intention through the movements of the other avatar when moving a virtual object (adapted from the paradigm of Quesque (Quesque et al., 2013)).

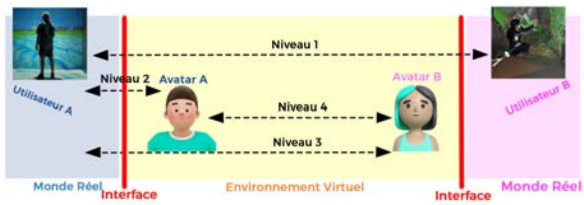

Figure 2: Interaction levels

6 Valuation of contributions

Two scientific experiments will be carried out during the course of the thesis, which will be technically supported by engineers from TORE (Lille) and TRANSLIFE (Compiègne, technical tests for platform connection, tracking, multimodal feedback). The first experiment will validate the fidelity of avatar representation (social intention, gestures, glances, positions, etc.) and the level of perception of remote users in this type of multi-site system, through an object manipulation scenario. A second experiment will measure the impact of social touch on cooperation by adapting the virtual object manipulation scenario with and without social touch. Ethics committees (Sorbonne Universités and Université de Lille) will be consulted before the experiments are carried out. Data will be secured and anonymized, as is already standard practice.

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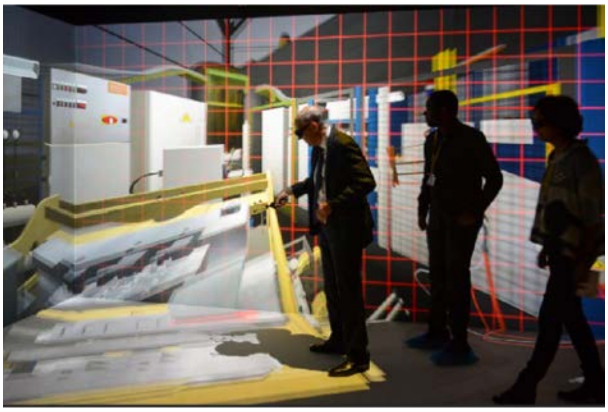
Figure 3: TORE



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Toward EEG discrimination of fingers movements during motor imagery vs passive movement

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Abstract

This study investigates the potential of passive finger movements as an alternative to motor imagery (MI) for the calibration of brain-computer interfaces (BCIs). Twenty-six participants performed both MI tasks and passive movement tasks involving finger flexion and extension, while their electroencephalographic (EEG) brain activity was recorded and analyzed. Brain activity in the α (8–12 Hz) and β (20–25 Hz) bands was significantly stronger during passive movement tasks compared to MI tasks. Additionally, task conditions and movement types had independent and significant effects. These findings suggest that passive movements could improve the accessibility and reliability of BCIs, particularly in applications requiring precise finger control such as extended reality applications.

1 Introduction

A brain-computer interface (BCI) records and analyzes brain signals, converting them into commands to control external devices (Kim et al., 2013). Non-invasive BCIs have applications in entertainment, such as video games, and healthcare, where they enable prosthetic control and assistive technologies like smart wheelchairs (Kim et al., 2013). They also have been increasingly investigated in the context of extended reality (XR). In virtual environments, BCIs can improve user interaction by enabling hands-free control, enhancing accessibility, and providing adaptive feedback based on real-time brain activity (Lécuyer et al., 2008). For example, BCIs have been used to navigate virtual environments, manipulate virtual objects, or adjust immersive experiences based on the user's cognitive state. A common approach involves imagining right or left hand movements to control the position of a character in a virtual environment.

Non-invasive BCIs often use electroencephalography (EEG) to measure brain activity. This is a painless process where electrodes are placed on the scalp to detect residues of electrical activity arising from neuron communication. This method is popular for its affordability, ease of use, and high temporal resolution compared to other neuroimaging techniques, making it suitable for research and clinical applications.

To generate brain signals that a BCI can reliably interpret, users must perform cognitive tasks that activate large groups of neurons, creating distinguishable patterns of brain activity. One widely used approach is motor imagery (MI), where users mentally simulate motor actions, such as moving a hand or foot, without physically performing them. This induces distinct patterns of activity in the motor cortex, making the corresponding EEG signals more recognizable for the BCI system (Morash et al., 2008).

BCIs rely on patterns of event-related desynchronization (ERD) and synchronization (ERS). During motor imagery or movement ERD occur in the alpha (8–12 Hz) and beta (13–30 Hz) bands within sensorimotor regions (Pfurtscheller et al., 2006) followed by an ERS rebound. Motor imagery tasks involving finger movements often result in lower BCI performance (Anam et al., 2019), primarily due to overlapping EEG signals from adjacent brain regions controlling different fingers. Additionally, extensive training and lower intuitiveness compared to other control methods limit user adoption (Alazrai et al., 2019).

Previous studies have shown that voluntary movements, passive movements and motor imagery produce similar ERD/ERS patterns in sensorimotor areas of the brain (Cassim et al., 2001). According to the literature, it is possible to use passive movements to calibrate BCI systems, offering an efficient alternative for the participants as they ensure the task is performed correctly, unlike motor imagery, which participants may find less familiar (Ang et al., 2011). In passive movements, limbs are moved by an external source, reducing cognitive and physical load.

Thus, passive movements are emerging as a promising alternative to motor imagery for the calibration of BCIs. This study aims to explore the use of passive movements for more complex tasks involving fingers, to determine whether this method can improve the accessibility and effectiveness of BCIs.

2 Materials and methods

Participants completed a 2-hour experiment where they: (1) performed MI and (2) experienced passive movements (applied by a custom-built exoskeleton).

2.1 Participants

Twenty-six healthy right-handed participants took part in the study (19 men, 7 women; age 22-48, $M = 29$, $SD = 6.7$). None of them had any history of neurological or psychiatric disorder.

2.2 Experimental protocol

Both motor imagery and passive movement tasks involved flexion and extension of the index, middle, and ring fingers, performed individually and together. The sequence of tasks was randomized, with 30 trials per movement type. Each trial included a random rest period (2.5–3.5 s) followed by a 6 s task. During the task, a visual cue of an animated hand playing a 3-key piano was shown. In the motor imagery condition, participants imagined the movements, while in the passive movement condition, an exoskeleton performed them.

2.3 EEG Recordings & Signal Processing

EEG data was recorded with 30 active electrodes and filtered using notch filter and a 0.5-40 Hz band-pass filter. Automatic artifact rejection, independent component analysis and common average reference were applied to limit artifacts. Event related spectral perturbation (ERSP) representations were computed with only significant effects displayed (see Figure 1).

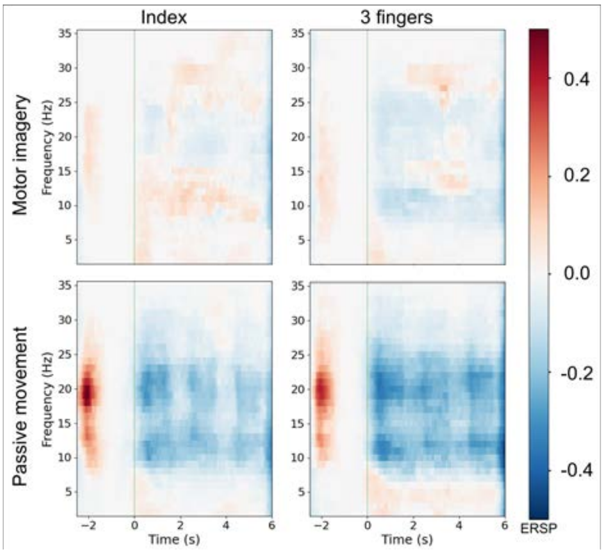

Figure 1: Grand-averaged ERSP at electrode C3 for MI and passive movement tasks for right index finger and three-fingers movements. Significant ERD are depicted in blue, while significant ERS are represented in orange.

3 Results

In the α (8-12 Hz) and sub-part of β (20-25 Hz) bands, a greater number of significantly stronger event-related desynchronizations (ERDs) were observed during the passive movement tasks than during the MI tasks. A repeated measures ANOVA on ERDS values between 8 to 25 Hz and 1 to 5 s after task onset revealed a significant effect of the experimental condition ($F = 19.77$, $p < 10^{-3}$, $\eta^2 = 0.12$) and the movement type ($F = 8.16$, $p < 10^{-2}$, $\eta^2 = 0.02$) on these values. However, the interaction between condition and movement is not significant ($F = 0.87$, $p = 0.45$, $\eta^2 = 10^{-2}$), indicating two independent factors.

4 Conclusion

In accordance with the literature, passive movements consistently elicited stronger contralateral ERD in the motor cortex compared to MI (Kaiser et al., 2011). It highlights the potential of passive movements as a reliable alternative to MI for BCI calibration, particularly in tasks involving fine motor control. We also observed significant differences in brain activity between various finger movements, suggesting that distinct neural activation patterns are associated with individual and combined finger tasks. These results seem promising, and could lead to an increase in the number of instructions usable in BCIs, opening up new prospects for their integration into XR technologies.

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Robust and Efficient AI Motion Capture

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Abstract

This document provides an overview of our research on developing robust and efficient AI-based Motion Capture (MoCap). While recent AI MoCap solutions have shown impressive results (Goel et al., 2023), they often require extensive post-processing and cleanup to produce usable assets, enabling downstream applications. These challenges arise from factors such as noise in 2D keypoint estimators, mismatches between predictions, and jitter in the output. Our work addresses these issues by introducing robust and temporally-aware neural pose solvers that maintain computational efficiency. We demonstrate that this approach can yield ready-to-use assets with minimal additional processing.

1 Introduction

The increasing demand for more realistic content in Virtual Reality (VR) applications has substantially increased the need for accurate digitization of human avatars to deliver compelling user experiences. Motion Capture (MoCap) technology remains the primary solution for VR developers, yet existing systems are often either prohibitively expensive (e.g., optical systems) or cumbersome (e.g., IMU-based suits) and can be sensitive to magnetic interference. Recently, advances in artificial intelligence (AI) have given rise to new MoCap approaches that extract motion data directly from raw video without requiring specialized suits. Although these AI-driven methods show promise, they frequently necessitate extensive post-processing by content creators and can demand significant computational resources.

In response to these limitations, our research focuses on enhancing AI-based MoCap by improving the robustness and efficiency of pipelines that derive motion from raw videos. We aim to produce ready-to-use, high-fidelity motion data that can be seamlessly integrated into downstream applications.

2 Approach

There are generally two main categories of AI Motion Capture (MoCap) methods: data-driven approaches, where human poses are directly regressed by neural networks (Goel et al., 2023), and implicit approaches, where pose parameters are retrieved by fitting a template mesh to 2D points estimated by an AI model (Pavlakos et al., 2019). While directly regressing pose parameters can be simpler, obtaining the large-scale datasets with 3D annotations required to train such models is often challenging. Thus, our solution takes a more practical route by fitting a 3D template mesh through the minimization of the equation below. In more detail, to estimate the human pose and shape at a specific time instance t, an objective function with two λ-weighted components is used, a data term, $\mathcal{E}_{data}$, and a prior term, $\mathcal{E}_{prior}$:

$$\underset{\boldsymbol{\beta},\boldsymbol{\theta},\mathbf{T}}{\operatorname{argmin}} \lambda_{data}\mathcal{E}_{data} + \lambda_{prior}\mathcal{E}_{prior}. \tag{1}$$

The data term is an L2 image domain distance error between the projections of the landmarks on each viewpoint $p := \{1, \ldots, P\}$ via each viewpoint's projection function π_p and the corresponding estimated keypoints $\mathbf{k}^p$:

$$\mathcal{E}_{data} = \sum_{p}^{P} \sum_{k}^{K} ||\pi^p(\boldsymbol{\ell}_k) - \mathbf{k}_k^p||_2^2. \tag{2}$$

To increase robustness against input noise in the estimated $\mathbf{k}^p$ keypoints, we propose a neural pose solver that explicitly models uncertainty during optimization. Drawing on likelihood-based formulations used in multi-task and robust stochastic optimization, we introduce a noise-aware fitting objective that adaptively captures a Gaussian uncertainty region (Albanis et al., 2023b).

Through extensive experiments(Albanis et al., 2023b, 2025), we demonstrate that this approach effectively handles noisy inputs and significantly improves overall performance and stability.

Capturing smooth motions from videos using markerless techniques often involves complex processes that incorporate temporal constraints, multiple stages of data-driven regression and optimization, and bundle solving over temporal windows (Albanis et al., 2023a, 2024). These processes can be inefficient and typically require the tuning of several objectives in stages. Instead, we propose an efficient alternative by retrieving the motion in a single stage, eliminating the need for explicit temporal smoothness objectives while still producing smooth motions. To do so, we leverage manifold interpolation between several latent keyframes (Albanis et al., 2023a, 2024), where the local manifold smoothness assumption allows the effective solving of a bundle of frames using a single code.

3 Conclusion

In summary, the proposed approach can generate ready-to-use assets from a sparse set of videos. By modeling uncertainty, we remain robust to noisy 2D keypoint estimates, while our bundle-solving approach improves temporal consistency (Albanis et al., 2023a, 2024). Importantly, this solution maintains computational efficiency throughout the entire pipeline. We address common AI MoCap challenges—such as jittery outputs, mismatched predictions, and complex multi-stage processes—using a noise-aware fitting objective and temporally consistent pose solvers. These neural solvers streamline motion capture to a single stage without sacrificing accuracy or smoothness. Experimental results confirm that our innovations minimize the need for extensive post-processing, enabling seamless integration into VR applications and other downstream applications. More results can be found in `https://moverseai.github.io/bundle/`.

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