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Mediating Experiential Learning in Interactive Immersive Environments

by

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Abstract

Simulation and immersive environments are gaining popularity in various contexts. Arguably, such interactive systems have the potential to benefit many users in a variety of education and training scenarios. However, some of these systems especially with the lack of skilled instructors are still faced by challenges of operational complexity, the incorporation of different technologies and features, and the limited availability of performance measures and feedback. Therefore, the design of these systems would benefit from integrating experiential aspects and essential educational aids. For example, users of such learning systems, especially the novice ones, can be better supported by a smoother learning curve, detailed guidance features, the availability of feedback and performance reporting, and the integration of engaging & reflective capabilities. In essence, we recognize a need to re-explore learning aids and how they impact design, usage, and overall learning experience in interactive immersive environments.

The goal of this dissertation is to mediate experiential learning in interactive immersive environments. This includes exploring existing and novel learning aids that would facilitate learning with improved engagement and immersion, enrich learners with insightful reflections, better support novice users' learning and training needs, and ultimately enhance the overall experience.

To achieve this goal, we utilized existing learning models and simulation-based training approaches and proposed a framework of learning aids to mediate learning in interactive immersive environments. Working closely with domain expert collaborators, we designed, implemented and evaluated four new interactive immersive prototypes in an attempt to validate the practicality of our aids. The first prototype, *NeuroSimVR*, is a stereoscopic visualization augmented with educational aids to support how medical users learn about a common back surgery procedure. The second prototype, *ReflectiveSpineVR*, is an immersive virtual reality surgical simulation with innovative interaction history capabilities that aim to empower users' memories and enable deliberate repetitive practice as needed. The third prototype, *JackVR*, is an interactive immersive training system, utilizing novel gamification elements, and aims to support oil-and-gas experts in the process of landing oil rigs. Our fourth prototype, *RoboTeacher*, involves a humanoid robot instructor for teaching people industrial assembly tasks. In our prototypes, we presented novel learning aids, visualization, and interaction techniques that are new to many of the current immersive learning tools. We conclude this dissertation with lessons learned and guidelines for designing with learning aids in future research directions that target interactive experiential environments.

Publications

Some of the materials, ideas and figures in this thesis have previously appeared in the following publications:

- **Mostafa, A. E.**, Ryu, W. H. A., Takashima, K., Chan, S., Costa Sousa, M., Sharlin, E. (2017). ReflectiveSpineVR: An Immersive Spine Surgery Simulation with Interaction History Capabilities. In Proceedings of the 5th Symposium on Spatial User Interaction (SUI '17). ACM, New York, NY, USA, 20-29. DOI: https://doi.org/10.1145/3131277.3132174 [Chapter 5]
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  DOI: https://doi.org/10.1145/3064857.3079152 [Chapter 5]
- **Mostafa, A. E.**, Inkpen, K., Tang, J., Venolia, G., Hamilton, W. (2016). SocialStreamViewer: Guiding the Viewer Experience of Multiple Streams of an Event. In Proceedings of the 19th International Conference on Supporting Group Work (GROUP '16). ACM, New York, NY, USA, 287-291. [Chapter 2]
- **Mostafa, A. E.**, Ryu, W. H. A., Chan, S., Sharlin, E., Sousa, M. C. (2016). Rethinking temporospatiality in everyday virtual environments. In the second IEEE Workshop on Everyday Virtual Reality (WEVR), Greenville, SC, 2016, pp. 36-39. doi: 10.1109/WEVR.2016.7859542. [Chapter 3]
- **Mostafa, A. E.**, Takashima, K., Sousa, M. C., Sharlin, E. (2015). JackVR: A Virtual Reality Training System for Landing Oil Rigs. In advances in Visual Computing (pp 453-462). Springer International Publishing. [Chapter 6]

- **Mostafa, A. E.**, Sharlin, E., Sousa, M. C. (2014). Poster: Superhumans: a 3DUI Design Metaphor, IEEE Symposium on3D User Interfaces (3DUI), vol., no., pp.143,144, 29-30 March 2014. [Appendix 2]

- **Mostafa, A. E.**, Ryu, W. H., Chan, S., Takashima, K., Kopp, G., Costa Sousa, M., Sharlin, E. (2017). Designing NeuroSimVR: A Stereoscopic Virtual Reality Spine Surgery Simulator. Research report 2017-1099-06, Department of Computer Science, University of Calgary, Calgary, Alberta, Canada, 2017. [Chapter 4]

- Ryu, W. H. A., **Mostafa, A. E.**, Dharampal, N., Sharlin, E., Kopp, G., Jacobs, W. B., Hurlbert, R. J., Chan, S., Sutherland, G. R. (2017). Design-Based Comparison of Spine Surgery Simulators: Optimizing Educational Features of Surgical Simulators. World Neurosurgery (2017). Volume 106, Pages 870877. DOI: http://dx.doi.org/10.1016/j.wneu.2017.07.021 [Chapter 4]

- Ryu, W. H. A., Dharampal, N., **Mostafa, A. E.**, Sharlin, E., Kopp, G., Jacobs, W. B., Hurlbert, R. J., Chan, S., Sutherland, G. R. (2017). Systematic Review of Patient-Specific Surgical Simulation: Toward Advancing Medical Education. Journal of Surgical Education (2017). DOI:10.1016/j.jsurg.2017.05.018. [Chapter 2]

- Quitter, T., **Mostafa, A. E.**, Norman, D., Miede, A., Sharlin, E. (2017). Humanoid Robots as Instructors for Industrial Assembly. In Proceedings of the 5th International Conference on Human Agent Interaction (HAI '17). ACM, New York, NY, USA, 295-304. DOI: https://doi.org/10.1145/3125739.3125760. [Chapter 7]

- Ryu, W. H. A., Dharampal, N., **Mostafa, A. E.**, Sharlin, E., Kopp, G., Jacobs, W. B., Hurlbert, R. J., Chan, S., Sutherland, G. (2017). Systematic review of patient-specific surgical simulation: Next step in advancing medical education. Oral Presentation at the Spine Summit 2017. [Chapter 2]

- Ryu, W. H. A., **Mostafa, A. E.**, Sharlin, E., Jacobs, W. B., Hurlbert, R. J., Chan, S., Sutherland, G. (2017). ReflectiveSpineVR: Incorporating nonlinear interaction history into surgical simulation design. Poster Presentation at the 2017 Sim Expo Conference. [Chapter 5]

- Ryu, W. H. A., **Mostafa, A. E.**, Dharampal, N., Sharlin, E., Kopp, G., Jacobs, W. B., Hurlbert, R. J., Chan, S., Sutherland, G. (2017). Design-based Comparison of Spine Simulation Models: Optimizing Educational Features of Surgical Simulators. Poster Presentation at the 17th Annual Scientific Conference of the Canadian Spine Society. [Chapter 4]
- Ryu, W. H. A., **Mostafa, A. E.**, Sharlin, E., Jacobs, W. B., Hurlbert R. J., Chan, S., Sutherland, G.R. (2017). ReflectiveSpineVR: Incorporating nonlinear interaction history into surgical simulation design, In Clinical Neuro Sciences Symposium, Calgary, AB, Canada, 2017. (Best Poster Award: 2nd place) [Chapter 5]
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Symbol	Definition
U of C	University of Calgary

Chapter 1

Introduction

We live in the information age where daily, many systems support people learning or training for specialized tasks. Indeed, immersive training environments and simulation-based education are gaining more popularity in various domains.

The design of such interactive environments generally aims at supporting learners by including educational features. However, many of these systems still ignore the needs of novice learners and lack innovative and effective learning aids. For instance, they often require a steep learning curve and neglect effective design guidelines suggested by (experiential) educational theories, resulting in a detrimental learning experience (e.g. [152] and [96]). Thus, a conclusive theoretical and practical investigation of learning aids for interactive immersive environments is required. We anticipate that further improvement to the design of simulation and immersive applications for education or training purposes would benefit all stakeholders and potentially enable effective and quality learning experience.

The goal of our research is to mediate learning aids within the contexts of interactive immersive environments, and attempt to validate how applying such elements would enable experiential learning. This also includes enriching user engagement and reflection, as well as improving interaction and overall experience of using immersive environments.

This research dissertation is structured as follows: we begin by summarizing background research relevant to learning theories, design and applications of simulation-based education. Then, we attempt to present a framework, inspired by theoretical investigations, that highlights the importance of integrating learning aids in interactive immersive environments. Following that, we present our approach utilizing experiential learning aids with specific case studies from the domains of surgical education, industrial assembly, and oil-and-gas exploration. Finally, we conclude with lessons learned and guidelines for designing with learning aids in future research efforts of interactive immersive environments.

1.1 Motivation

The lack of intuitive learning aids within interactive immersive environments and applied simulation is the main motivation for this research. While existing works provide advance theoretical insights into learning and the design of training systems, many past studies focused on general educational concerns such as having good content, knowledgeable tutor, or support for collaboration [8], [120], and [137]. They seem to have limited support for experiential aspects and essential learning aids such as innovative guidance and reflective capabilities in their design of interactive systems. In this section, we argue that re-visiting such aids could particularly improve the overall learning experience within interactive immersive environments, especially because such aspects have been successfully utilized in other domains including games and simulation. Therefore, exploring the learning aids possesses the potential to positively impact user's interaction and enrich the overall learning experience.

Current interactive immersive learning environments may be strengthened and benefit from the following aids:

1. Innovative guidance features such as on-demand dynamic hints or temporal trajectories (improved visual tutors)
2. Simplified interface and interactions involving careful coordination between multiple devices and techniques (better usability)
3. Integration of experiential aspects such as situated learning, engagement, and immersion
4. Support of proper performance reporting and reflective feedback

5. Smooth learning curve especially for novice users
6. Exploring cheap technology where learners are able to afford their own simulations
7. Enhanced visual representation of the learning content

We decided to re-explore learning aids within the context of immersive environments because they have the potential to mediate experiential learning and enable quality experiences. Also, because the recent advances in technology enable such an exploration. For example, in a typical immersive firefighting training scenario, users may be limited to performing specific actions that constitute the firefighting task. Users may follow a predefined sequence of operations without having the flexibility to re-order certain events or manipulate the rate at which they occur. Alternatively, the design could leverage the unique immersive aspects by giving users flexible learning aids and temporospatial interactions. For instance, with the ability to manipulate time or control the action rate making it slower or faster as needed, users could gain better reflection, engagement, and transfer of learning. In essence, current practices of interaction design within the context of immersive environments poorly utilize or even ignore experiential learning elements. This factor could limit user engagement, lead to poor situated awareness, or weakly support insightful reflections, and ultimately impact the overall experience.

In general, when we integrate learning aids in our design, we should not consider learners as mere users; that is ignoring their skill set or background knowledge of the topic. We should also not ignore utilizing the inherent spatiality of the immersive environment. Rather, we should strive to conform to outcomes of education theories including suggestions to encourage critical thinking, engagement and experiential learning. Consider the scenario of students learning about history in a more active way by time travelling and experiencing historical sites as if they were living in that era. As well, immersive training tools that replicate the operating room and allow medical learners to repeatedly practice and be aware of their past interactions over time (more about this example in Chapter 4). Such innovative experiential applications can be powerful in supporting transfer of learning and the overall educational experience [159] and [187].

1.2 Hypothesis

We hypothesize that by re-exploring learning aids within the context of immersive environments, users' interactions will be enriched and they would gain better learning outcomes. Users will be more engaged and could reflect deeper and gain greater understanding throughout their experience. Furthermore, incorporating novel educational aids and temporospatial elements into immersive and virtual environments will provide users with improved learning experience.

1.3 Research Scope and Questions

Our research involves aspects from multiple domains that relate to the study of educational aids for supporting simulation-based education and immersive training. Our exploration of such aids for design of interactive immersive systems involves theories from psychology, gamification, interaction design, human-computer-interaction, virtual reality, and education.

To assess the hypothesis of this PhD research, we attempt to re-explore educational aids and temporospatial elements to enrich user engagement and the overall learning experience within interactive immersive environment contexts.

This dissertation main research questions are:

1. **What innovative learning aids are there for enhancing interaction within immersive environments? And why do such elements have the potential to enable experiential learning?**

   We aim to re-visit and identify novel educational design elements and learning aids that could enrich interaction and facilitate learning within immersive and virtual environments by: (1) exploring specific domains (e.g., games, education) that have successfully utilized such aids in their design, and (2) studying theories of education, from fields such as psychology, philosophy and interaction design. The answer to this question is detailed in Chapters 2 and 3.

2. **How could the re-exploration of learning aids mediate experiential learning and improve design and usage of interactive immersive environments?**

   Here, we plan to investigate and assess existing and novel elements of interest through a set of prototype implementations. We study how learning aids can be utilized to augment immersive interactive tasks. We reflect on available interaction possibilities and how these impact users' perceptions and experiences. Then, we validate the value of educational aids through four implementation case studies of the following domains: surgery, oil-and-gas, and industrial assembly (as detailed in Chapters 4, 5, 6, and 7).

3. **What are the guidelines for future design efforts of building immersive education- and training- based environments?**

   As the final part of this research, we attempt to generalize lessons we learned through users' feedback. We reflect on how the resulting guidelines have the potential to improve future interaction design research efforts that target immersive and virtual learning environments. Our discussion and guidelines are detailed in Chapter 8 and 9.

1.4 Methodology

In an attempt to address the aforementioned research questions, we propose a re-exploration of learning aids within interactive training and educational contexts. We adapt a gamification (experiential) approach to human-computer interaction that focuses on empowering users and the overall learning experience.

The following is a summary of the major phases involved in our approach.

Literature Review: we study the literature to identify and discover existing and novel learning elements and build on theories from other fields including psychology and education. Moreover, we seek inspiration from studying how such learning elements as reflective feedback and guidance trajectories have been successfully considered in various domains (e.g., games and simulation). We also explore how applying these elements would facilitate experiential learning and enrich users' interactions within immersive environments.

Low-Fidelity Design: we use sketching and storyboard techniques [28] to develop and refine our ideas and to determine the most optimal method of prototyping them in the various scenarios.

Implementation: we design, develop, and evaluate prototypes to validate our research ideas in practical contexts. Here, we also explore how learning elements could be applied and how they impact a user's interaction within immersive practical contexts. This is an iterative step with many degrees of refinement, which involved multiple meetings and discussions with respective expert collaborators. To ensure a realistic evaluation, potential users are invited to engage with the developed prototypes.

Lessons Learned: based on our exploration and the feedback we receive, we attempt to generalize and document recommendations and lessons we learnt to improve relevant future efforts.

Case Studies of Learning Aids

Here, we validate particular learning elements in practical contexts through simplified case studies from the domains of surgery, industrial assembly, and oil-and-gas. For our evaluation, we collaborated with domain experts (e.g., surgeons and engineers) and involved potential users whenever possible to critique our design and gather feedback. We aim to enrich users within these domains with learning aids and improved interactions. We anticipate that, with technological advances and proper training, users from those domains will realize the benefits of learning aids. Users will recognize how such elements can improve engagement and reflection during interactions and how they mediate experiential learning. The following are the practical case studies we have pursued in this dissertation:

- **Back Surgery Simulation**: Through two immersive prototypes, we explored how various educational aids can support surgery trainees by learning and practicing the procedure of pedicle screw insertion (Chapters 4 and 5).

- **Landing Oil Rigs**: Based on discussions and meetings with an oil-and-gas expert, we prototyped an interactive immersive simulation empowered with learning aids to train experts on landing oil rigs (Chapters 6).

- **Industrial Assembly with Humanoid Robots**: In this exploration, we studied how people can assemble an object while tutored by a humanoid robot. The goal is to address the lack of skilled human mentors and support individualized learning (Chapters 7).

1.5 Research Contributions

The aim of our research is to mediate experiential learning within the context of interactive immersive environments. In general, we aim to provide a better understanding and validation of existing and novel educational elements and how they facilitate learning and impact user interaction. In other words, our research is expected to narrow the current gap resulting from the limited exploration of experiential educational aids in immersive environments.

The main contributions of this research are:

1. **Deeper theoretical insight and better understanding of how educational aids and temporospatial elements can be incorporated into a three-dimensional context.**

2. **Design, development, and evaluation of a 3D simulation prototype aiming to facilitate learning of a specific back-surgery task. This includes simplified interaction capabilities and novel features (i.e., landmark trajectory hinting, step-by-step guidance, post-simulation feedback and 3D/haptic interfaces).**

3. **Design, development, and evaluation of a fully immersive surgical training prototype. This includes novel interaction history capabilities to support repetitive practice as a key**

element in surgical-based training. This project follows the insight of a design study that explores nonlinear interaction history representations and their potential as effective educational aids.

4. **Design, development, and initial evaluation of an immersive virtual reality prototype aiming to simplify learning and experiencing the process of landing oil rigs. The implemented prototype replicates a dynamic and complex environment, simulating weather/sea conditions and including novel features (inspired from games).**
5. **Design, development, and evaluation of a humanoid-based prototype exploring how robots can be instructors teaching industrial assembly tasks. This is especially valuable when there is a lack of human mentors or because of environmental challenges.**
6. **A summary of lessons learned and reflections that could guide future research efforts involving learning aids. This includes a set of temporospatial design guidelines and heuristics tailored to mediate experiential learning within immersive environments.**

The reminder of this dissertation is structured as follows: we begin by reviewing existing research from the education literature as well as from other relevant domains (Chapter 2). We then present a framework focused on exploring learning aids in immersive environments (Chapter 3). After that, we detail the main technological explorations of this research as a set of prototypes with their evaluations (Chapters 4, 5, 6, and 7). Finally, we discuss our results and conclude this dissertation with recommendations for future efforts of mediating learning in immersive environments (Chapters 8 and 9).

Chapter 2

Background

Many immersive simulation and interactive systems enable people to attempt and practice specific tasks that are often risky, expensive, or not feasible to be performed directly. Such systems have been developed for various domains particularly to support learning and training. In this chapter, we review the literature of simulation-based learning and report on existing explorations of interactive immersive educational systems from various domains. This includes how the different fields of surgery, robotics, games, and human-computer interaction have considered learning aids in their design of educational systems. Finally, we review existing research that relate to innovative utilization of temporality as a unique learning aid.

2.1 Introduction to Simulation-based Learning

Simulation-based learning, education, or training all refer to some sort of context/scenario replication with the goal of supporting learning and training [168]. As an emerging field, some academics called for the need of having simulation specialists and to professionally recognize them, especially those who can build training and educational environments [120].

Many fields including surgery, military, engineering, and aviation have attempted to explore simulation as a basis for developing learning environments (See section below). On one hand, many researchers, particularly within the medical field, consider simulation-based learning as a way to develop users' knowledge, skills, and attitudes [89]. In a study conducted with science students [153], the authors have developed an exploratory simulation-based game learning environment for observing science experiments, and their preliminary findings hint at effectiveness of the simulation environment. The potential of simulation-based learning goes beyond skill training and can be perceived as a platform that provides a valuable tool in learning to mitigate ethical tensions and resolve practical dilemmas [126]. On the other hand, a research investigation by Bell and others have examined the effectiveness of simulations as training tools [12], and highlighted that many of the existing work utilizing simulation painted a mixed picture with regards to effectiveness. As the authors stated, *"all that can be concluded is that this particular system did (or did not) work, but it is unclear exactly why."* Therefore, a careful re-exploration of educational aids is needed to mediate experiential learning in interactive immersive environments.

2.2 Medical Education and Training

Simulation-based learning has been extensively explored within the medical field (e.g., [175], [176], and [43]). The emphasis is now shifting from the technology of simulation towards partnership with education and clinical practice [199]. This highlights the need for an integrated learning framework, where knowledge can be acquired alongside technical skills and not in isolation from them. Ideally, such a framework should build on existing efforts that aimed to support the design of surgical simulation systems by focusing on the common issues of identifying training needs and the lack of systematic methodology for system design and evaluation [40]. In this section, we review key works related to the use of simulation to support medical education and training with particular emphasis on the role of virtual reality immersive environments.

2.2.1 Immersive Environments and Surgical Education

It is clear that enthusiasm and demand for simulation-based education exist in medical and surgical education. For example, Murphy and others presented a discussion of why simulation has the potential to support and complement medical training and simplify the problems of reliance on actual patients and error tolerant environments [162]. Fanning and Gaba have attempted to describe simulation-based learning as an educational tool and discussed theories and applications to the surgical domain [69]. For a more extensive review, we suggest referring to [36].

Existing research discussed the potential benefits of virtual immersive environments for learning (e.g., [42]). Along the same line and with regards to the medical field, Simulation and virtual reality has proven to be effective to improve surgical training [58]. Also, a survey has studied the effect of 3-Dimensional simulation on neurosurgical skill acquisition and surgical performance [33]. The authors highlighted that 3D simulations are useful supplement to training programs and stressed the need for improvement in surgical performance to warrant large-scale investment in this technology. Also, Dawe et al. presented a systematic review of skills transfer after surgical simulation-based training [44]. However, surgeons not only need effective simulation tools, but they also need flexible interaction capabilities and effective feedback measures that allow them to repeatedly practice the simulated procedures as needed (e.g., [9], and [226]). Surprisingly, most prototypes fail the requirement to keep history of users' actions and allowing them to retrace their steps, according to Shneiderman [211].

Virtual reality simulations especially that utilize stereoscopic displays are common in surgery [141]. Indeed, various computer simulations have been developed for numerous medical and surgical specialties such as general surgery (e.g., [144]), vascular surgery (e.g., [2]), neurosurgery and critical care medicine (e.g., [180] and [236]), and have been shown to improve surgeons' skills [209] and [180]. Along the same line, Ekkelenkamp et al. presented a systematic review of GI endoscopy simulation for learning and training purposes [61]. The authors concluded that the use of validated virtual reality simulators particularly for training novice medical users would accelerate the learning of their skills. In addition to medical simulations, serious games and augmented reality applications have been also common for medical education and surgical skills training [84].

Our work in this dissertation utilizes the context of spine surgery. Therefore, we attempt to review relevant work in this part. Immersive simulation systems for training spine surgery including the Pedicle Screw Insertion (PSI) procedure have been researched from both commercial and academic sources [166] and [182]. For instance, Klein and others proposed a CT-based patient-specific simulation for pedicle screw insertion [122]. Alaraj and others have explored the role of virtual and augmented reality spinal simulation utilizing the commercial Immersive Touch simulator for neurosurgical training [3]. More recently, a study investigating the use of patient-specific volume rendering combined with projected fluoroscopy (X-ray) for training junior surgeons about the pedicle screw insertion procedure was conducted [248]. The authors concluded that it is helpful to support trainee with X-ray projection as it can enhance their skills. Our work extends these works by focusing on improving usability aspects including simpler interaction capabilities and educational features in order to support novice surgeons while training the spine surgery simulation.

2.2.2 The Role of Haptics

Clearly, effective rendering is important in surgical simulation. Existing research also highlighted the importance of haptic feedback as a major contribution for achieving effective training systems [34]. Along the same line, a study by Waran and others has explored the use of 3D printed models from imaging data for the purpose of surgical training [238]. In another study, the use of 3D printing for supporting surgery has been examined and it has been found that it can ease the difficulty of complex spinal surgery [148]. Such examples reflect the importance and focus on having improved graphics and haptic while building surgical simulation. However, user experience elements are often poorly explored (see [96], [97] and [142]), so we argue that special user interface design is needed. Therefore, we focus on improving the simulation as a whole particularly the user interface elements, the supported interaction, and the system usability.

In summary, existing research acknowledge the importance of simulation for learning and practicing surgical procedures. However, the limited focus on simplifying user interaction and the overall experience in such simulations calls for an effort to carefully explore and design an immersive simulation with innovative educational elements and simplified interaction capabilities especially for novice medical trainees.

2.3 Learning with Robots

It is common for people to learn from human instructors and teachers. Surprisingly, humanoid instructors can also assume the role of teachers and can particularly be valuable in many situations (as we explore in Chapter 7). In this section, we overview key existing research that relate to robotics and learning (Refer to Appendix A for background of this domain).

The use of robotics in training and education may follow patterns of adoption in other areas of work. Research on technologies that enable the integration of new forms of media interaction, such as intelligent tutoring systems [184], social robots and virtual agents [131] in education and physical rehabilitation [130] are instructive.

Technology-enabled, competence-based, training has been successfully used to train doctors to perform psychomotor tasks, such as those used in laparoscopy (e.g., [91]). Similarly, virtual and augmented reality are employed in the training of mechanical assembly tasks (e.g., [125]). In such initiatives, simulated representations of a patient, or mechanical system, were used, with students learning and performing tasks within a simplified, artificial environment. In essence, students demonstrate more rapid adoption of tasks when interacting with fidelity simulated control interfaces, and when manipulating tangible physical mechanical objects as part of the learning process [21].

Robots have been shown to help learners overcome language barriers by combining the use of gestures with spoken commands [72], and can be effective as tutors providing social gestural cues to students [219]. Social gaze in robot interaction improves spatial management functions involved in mechanical assembly operations by directing attention, and movement, with nonverbal cues that supplement or augment verbal, and written, instructions [71]. In typical human-robot instruction scenarios, humans interact with robots using human movement to train trajectories and movement for the robot [16]. This dissertation, in part, explores the other side of the interaction. The robot leads the interaction, and guides the human worker's movement during the assembly process (Chapter 7).

In industrial training and instruction, instructors are generally drawn from the ranks of personnel who are expert in a given trade. This approach can lead to shortages of available instructors capable of training large numbers of new workers, leading to a reliance on distance learning, print, and electronic resources, to extend individual instruction [167]. More recently, Quitter et al. explored how a humanoid robot may assume the role of instructor for teaching a basic industrial assembly task [187]. Their approach enables students to learn to assemble mechanical components in-situ, guided by gestural, verbal, and graphic instructions and feedback provided by a Baxter robot, with the goal of creating a fully, and correctly, assembled device.

2.4 A Human-computer Interaction Perspective on Designing Learning Systems

In this section, we present existing efforts concerning the design of effective learning environments with a focus on works from the fields of human-computer interaction and interaction design.

Various researchers have looked into unique aspects for the design of learning envrionments. The early work by Barker [8] disscussed how interactive learning can be designed, what are the nature of environments needed to support it, and how interactive learning supports knowledge acquisition. Along the same line, the learner-centered design is a common approach where users are considered as learners and where systems are designed as cognitive tools that foster learning and support skill development [105]. More recently, Cannon-Bowers and Bowers presented a framework with questions and variables that must be addressed in order to optimize the design and use of synthetic learning environments in training [29]. In contrast, existing research highlighted that careless design of learning systems may have detrmintal effect on the learners [152]. In this regard, novice learners may suffer cognitive load if the interaction required to use the system is complex or if the content representation is poor.

Current practices of designing educational systems generally focus on key elements such as guidance, feedback, and animation to support effective learning. The importance of such elements is highlighted by early research. For example, Rieber mentioned that the representation of feedback matters within learning environments as people may prefer graphical animated feedback over text [190]. A more recent study explored how adults learn and interact in a simulated environment with animated feedback supplemented with brief multimedia explanations of the content [191]. Results showed significant differences for both the use of the explanations and simulations containing graphical feedback in helping participants gain both implicit and explicit understanding of the science principles. Finally, Billings has explored the efficacy of adaptive feedback strategies in simulation-based training, by providing little feedback at first that becomes more detailed gradually over time [17].

To support discovery in learning environments, the design of systems may benefit from the integration of reflective interaction history features. Such features could help generate hypothesis, map previous learners' knowledge and support awareness [188]. This is also highlighted in the early work by Plaisant et al. [183] where they discussed the challenges of implementing learning histories and presented a first implementation of learning histories for a simulation-based engineering learning environment. In a more recent study, a modified simulation that supports learning history was used to evaluate the effectiveness and efficiency of a learning process that takes place in a dynamic simulation [178]. The findings relate having better performance to the learning history recording features that made available to users.

2.5 Gamified and Creative Learning

Gamification involves applying game design elements in non-gaming contexts [51]. Games can and have been used to support education with unique aspects including innovative knowledge representation, the potential to captivate users' attention, and with creative ways to guide learners [54]. In this section, we review how games can be beneficial to learning, how they can be considered experiential mediums, and what elements are there for the design of educational games.

Extensive research have explored gamifying education by bringing gaming elements to the design of learning environments. Early research by Amory et al. [4] identified game elements that were useful and interesting for their teaching environments and presented a model to link pedagogical issues with the identified elements. Also, it was shown that learners of gamified systems can observe consequences of their actions and reflect on their decisions [106]. Shaffer et al. have discussed why and how games could change the way we learn [210]. They mentioned that games as simulated experiences encourage social practices and argued for an approach to the design of learning environments that builds on the educational properties of games, but deeply grounds them within a theory of learning. More recently, Schrader et al. reported that educational games can be beneficial for learning as they have the potential to better captivate learners' attention for along time especially if they are designed to reduce cognitive load while also enabling virtual presence [203]. On the contrary, few existing research had claims about the usefulness of games for learning (e.g., frequent use can exacerbate negative psycho-social tendencies, be addictive and have health implications) [147]. Along the same line, El-Masri and others argued that while gamifying education can be useful, it is still limited because of difficulty of adoption in course design and by students. The authors proposed seven principles for better design of gamifying education [62].

The experiential learning approach can be applied to games and give learners the opportunity to apply knowledge within the virtual world. The early work by Thatcher investigated experiential learning, highlighting the role of simulations and games in promoting learning [223]. Kiili [116] has presented an gaming model based on experiential learning theory, flow theory and game design. The author highlighted the importance of providing immediate feedback, clear goals and challenges that are matched to learners' skill levels. In a study conducted by Vogel and other researchers, they found that games and simulation can be more effective for learning and are more dominant for cognitive gain outcomes versus traditional teaching methods [233]. Researchers discussed how games could be a space for learning that would affect future schooling models [213]. In this regard, it can be valuable to follow a structured evaluation approach as proposed by Freitas and Martin [48]. The authors have introduced a four-dimensional framework for helping tutors evaluate the potential of using games- and simulation- based learning in their practice, supported by practical case examples.

Game design elements such as motivation, flow, narrative context, and multisensory cues can contribute to building effective learning experiences. In this regard, researchers have examined different game types and elements and provided suggestions to guide the design of educational games (e.g., [4] and [56]). In addition, many researchers were driven by the need to guide the design of educational games and proposed relevant frameworks accordingly. For instance, Mansureh et al. [115] presented a systematic review examining educational games and aiming to identify theoretical educational approaches that have been considered in games, with guidelines on how this may support future research effort on developing educational games. Also, Kiili et al. based their proposal upon associative, cognitive and situative learning theories, including engagement and pedagogic elements with a focus upon feedback and flow principles [117].

Guidance is another learning aid inspired from games that can especially support novice learners, by reducing cognitive stress in terms of task complexity and difficulty. The effectiveness of this approach is supported by research in the field of cognitive load theory (e.g., [121]). Moreno [152] concluded from a literature review of studies comparing pure discovery learning with guided forms of learning that "the debate about discovery has been replayed many times in education but each time, the evidence has favored a guided approach to learning" (p. 18). Along the same line, Kirschner and others highlighted that only designing minimal guidance features during instruction may not be sufficient [121]. The authors added that one of the potential threats not only of educational computer games but of all discovery-based, problem-based, or experiential learning environments is that they make heavy demands on learners' working memory capacity by requiring unnecessary cognitive load that exceeds the limitation of working memory. For example, learners' attention is needed to manipulate the game and control experimental tasks through motor actions that perhaps are delayed in space and time in the gaming environment. Therefore, careful design of game-based education is needed.

2.6 Immersive Environments Impact Learning

The use of immersive technologies including virtual and augmented reality is common for supporting learning and training in a variety of contexts including nursing [118], learning of mathematics and geometry [114], engineering [1], science (e.g., [153]), and medical education & surgery training (e.g., [24]).

Virtual reality (VR) could help to improve performance and conceptual understanding on a specific range of task, but there is still limited understanding of how VR could enhance the learning outcomes [119]. In this regard, many researchers have attempted to study the role of immersive environments for learning. Early research [151] examined VR and how it relates to education. The paper identified various phenomena that may constitute VR and the conceptual attributes which separate VR from interactive multimedia, making it more of a learning environment rather than an educational tool. Furthermore, the authors examined implications of VR for educational theory, methodology and practice, focusing on case studies of VR research in education and society. Also, Mantovani [140] discussed potential and challenges for the use of 3D immersive environments in education and learning, highlighting aspects of VR that relate to education theory with guidelines for future VR design efforts. In the work of [177], the authors analyzed variety of virtual and augmented reality learning environments, showing that such immersive applications can motivate learners and enable quick and engaged learning. For more extensive reviews about immersive environments and learning, see [129], [146], and [76].

Games and simulation share similarity, but existing research highlighted few minor differences between them especially when it comes to learning [85]. Prensky [185] argued that depending on what it is doing, a simulation can be a story, a toy, or a game. He added, that a simulation needs additional elements to be a game such as fun, winning, competition, etc. In lay terms, simulations differ from games in that they are often linked to replicating scenarios from real life, with no need to include gaming elements such as fun and play. Along the same line, some researchers have examined if a simulation-based approach would be better to enable learning than games.

According to the results of a study conducted by Vogel and others [232], they found that games designed to enable learning should rely on a simulation-based approach rather than the linear and structured presentations in traditional gaming environments.

One of the unique aspects of immersive environments is immersion as discussed by Psotka, highlighting how it contributes to training and learning [186]. Similarly, Dillenbourg et al. [55] mentioned specific VR features that justify use of immersive environments for learning and how some of these features guarantee pedagigical effects. More recently, De Freitas et al. [49] discussed learning immersive experiences, highlighting how presence and the multisensory features of VR empower learning and enable to simulate complex (social) interactions. Along the same line, Dalgarno and Lee [42] presented a comprehensive review of the learning affordances of 3D virtual environments including aspects of their representational fidelity and aspects of the learner-computer interactivity they facilitate. Another work highlighted that designing for immersion, visual cues, and the temporal-spatial relations aid in the transfer of knowledge by supporting building an association between what the learner is doing (in the simulation) and the long-term (episodic) memory [113]. More recently, The work by Fowler [74] builds upon Dalgarno and Lee model of learning in 3D virtual environments while attempting a more pedagogical description in a hope to better design learning activities in such 3D environments.

Another unique aspect of immersive and simulation learning environment is that they enable exploratory and experiential learning [47]. The design of such experiences depends on and benefits from having effective interactivity. In the work of Roussou [198], she examined how immersive learning worlds embrace the constructivist approach to learning, collaboration, and narrative development, and how their effective design utilizes the strengths of virtual reality: a combination of immersion, telepresence, immediate visual feedback, and interactivity. This is similar to the work of Huang et al. [102] where they examined learner's attitude towards virtual environment also following the constructivist approach. Another key aspect of immersive environments is that they enable situated learning [45] and support transfer of spatial knowledge [237].

Immersive environments can include simulation of virtual users and avatars to emulate collaboration within the virtual space. Such multi-user immersive environments also have the potential to support situated learning that involve multiple learners in the same immersive space [134]. Augmented reality also enables immersive collaboration and has been used to support education [7]. In a study conducted by Becca and others [57], the authors reported that teachers and students found the technology-mediated narrative and the interactive, situated, collaborative problem solving affordances of the AR simulation to be highly engaging. They also noted that AR simultaneously presented unique technological, managerial, and cognitive challenges to teaching and learning.

2.7 Temporality as Educational Element

The design of temporality has the potential to enrich learning environments with reflective features and temporospatial capabilities. In this section, we review relevant works focusing on people's perception of time as well as how temporality can be designed to support anticipation, efficiency, and creativity. Finally, we review a unique potential of temporality to support reflection and repetitive learning.

2.7.1 Perception of Time

The importance of time in our understanding of the universe is reflected in early and recent discussions by scientists and researchers from different fields such as physics, psychology and philosophy [245]. Generally, we do not have a dedicated (internal) sense for perceiving time. However, much of our perception is informed by spatial cues and metaphors. Such spatial cues and metaphors indirectly support our understanding of time and enable us to successfully interact with the dynamic events that we encounter.

Early discussions among physicists revolved around two contrasting viewpoints of describing time as either an absolute or relative dimension. Newton talked about time-and-space as absolute dimensions and maintained that time is an independent dimension of the events, in which they occur in sequence. Modern views by Einstein and quantum theories, on the other hand, have referred to time from a relativistic point of view, noting that our conception of time varies according to where and how we observe it [245].

The philosophy and psychology of time also provide various theories about how we perceive time (with space), and how our minds provide us with a way to track and realize it. In his classical work, The Principles of Psychology [107], W. James observed that our perception of time has some analogy to our perception of space. In this regard, he expressed, "*Date in time corresponds to position in space; the original experience of both space and time is always of something already given as a unit, inside of which attention afterward discriminates parts in relation to each other*". More recently, Boroditsky [20] elaborated on how we may understand time through spatial metaphors by referring to cognitive and linguistic perspectives. In particular, she investigated whether the abstract domain of time gets its relational structure from the more concrete domain of space, arguing that: (1) the domains of space and time do share conceptual structure and (2) spatial relational information (e.g., up and down) is just as useful for thinking about time as temporal information. She also referred to two main schemas with regards to spatiotemporal metaphors; the time-moving metaphor in which the individual is seen as stationary and objects come toward him or her, and the ego-moving metaphor in which the individual is moving but objects are stationary. As part of this proposal, we will show how these spatial properties of time may be exploited by designers of interactive systems, for example, by utilizing the virtual space in front of or behind the user to indicate possible actions to be performed.

On the contrary to how space informs our perception of time, some work in psychology with particular relation to neuroscience attempts to relate our perception of time to our internal biological clocks and cognitive behaviors [18, 60]. Similarly, Le Poidevin [128] argued that "*even if all our senses were prevented from functioning for a while, we could still notice the passing of time through the changing pattern of our thought as if we have a special faculty, distinct from the five senses, for detecting time*". Galton [79] discussed factors that limit our spatialization of time, by claiming that not all spatial attributes can be used to refer to time. These works provide insight that could guide our exploration and identification of temporospatial elements when it comes to supporting the design of interactive learning systems.

2.7.2 Time Design

Time as a reflective element is heavily explored in the design of artifacts and artistic objects. For instance, the architecture of shopping malls is generally designed to experience loss of time and accordingly we barely see in them any devices that display time. Other artifacts such as statues adapt an artistic approach to time design as they often reflect on historical times or events [193].

Other disciplines investigate aspects of time design in different ways. Socially, Hörning et al. [99] explored the role that technologies play in timing social actions. The authors claimed that we may suffer from a paradox in which we constantly save time by using better and speedier technology, but in the end we do not have more time than before. The field of interaction design, on the other hand, attempts to focus on temporal design as a key aspect that affects the creation of intuitive behaviour and interaction.

When it comes to interactive systems, while games explored very creative temporospatial design (e.g., Braid [214]), only few researches have looked into this aspects of immersive systems as a design space that needs to be charted and methodologically validated [242].

Goals of Temporal Design

Designing for task efficiency has been a clear goal of time design [37]. However, Hallnäs and Redström [90] explored time design to support reflection and learning, essentially aiming at “putting back time” into design after it has been ignored for efficiency concerns. They introduced “slow technology”, inviting for reflection to be inherent in the design and proposed beneficial effects on learning and understanding.

Supporting anticipated user interactions is another goal of time design, which can also be regarded as a learning aid that guides user’s interaction. Along the same line, Bret Victor emphasized the usefulness of time abstraction in predicting system’s behavior and anticipating the various configurations, without trying each of them [230]. However, in time design, it is note worthy to realize that it can be hard to avoid the challenges associated with design for change and uncertainty [225]. Our exploration of temporospatial elements similarly aims at enhancing user engagement by supporting flexible interactions that could assist in learning and reflection.

Creative Use of Time

Time has been part of creative usage in the entertainment domain including film, TV and games. Traditional storytelling usually manipulates the sequence of events/actions to draw attention, to set and emphasis, to introduce different explanations for events, and to highlight the small differences between fiction and reality. Furthermore, the vast majority of movies tell stories of different times and show events carefully orchestrated to follow a narrative timeline. Such movies sometimes involve aspects of temporospatial manipulation such as scaling and compression where, for instance, events may take longer to happen than in real life (e.g., bullet-time as in Matrix [246]). An example from TV is the series 24, which takes the unique approach of portraying time passing in the series in line with the time passing for the viewers (i.e., a minute is a minute for both the viewers and the actors). We argue that such unique and innovative utilizations of temporality can be leveraged to aid the design of learning environments.

Games utilize time design with a more active approach with regards to interaction. Wei et al. [242] explained the effects of providing time control to players. These include overcoming challenges and increasing the level of pleasure by rewinding the game (e.g., Prince of Persia, Max Payne, Braid, Quantum Break), emphasizing aspects of a fight (e.g., magnifying the scale of impact of a kick), and providing faster movements (e.g., teleporting [244]). Another utilization of time in games is the introduction of a temporal device like a ticking clock that intensifies the challenge, and help forming the emotional experience of the player. Despite the wide use of time in games, game design books lack discussion of temporality, possibly because they interrelate temporality and narrative [202].

Similar to time, space is an important element that can be utilized in creative applications.

Within the context of creative installations, Benford et al. explored interaction trajectories as journeys that utilize time-and-space and explain the nature of complex user experiences [13]. In games, space is also important in the understanding of game design and game experience [242]. It can be manipulated for particular benefits and we argue that this may hold true for immersive virtual learning environments as well. For instance, objects (e.g., music) can be attached to specific locations/regions and can be designed to appear only at certain times. As a result, the appearance of an object might notify the learner during interaction, indicate what would be the next action, or suggest a new direction.

Temporality in Interaction Design and HCI

The field of human-computer interaction (HCI) generally considers time to be subjective; similar to a mathematical entity, it can be measured, added, quantified, and applied [208]. Regarding the representation of time, design has utilized visual concepts to simplify interaction [227].

A workshop at CHI 2013 focused on exploring different ways of thinking about time as a resource for research and innovation [133]. For instance, Faconti and Massink proposed the concept of continuity to encourage thinking of interaction over time intervals rather than at discrete points [68]. Next, we examine various applications of temporality, by highlighting how such applications have incorporated aspects of time design in their implementations.

Spatial Implementation of Temporality

Space is limited in the context of standard desktop tasks due to the limited onscreen area for interaction. Other contexts such as Virtual Reality (VR) are inherently rich in space since they often simulate processes that occur in 3D space over time. However, only a few systems within this spatially-rich domain integrated creative temporospatial elements in their design.

The work of Stoev et al. [218] represents the first attempt to enable exploration of past events of historical data by proposing a visualization toolset with time manipulation capabilities. Sugimoto et al. [220] implemented a teleoperation interface inspired by temporality to augment users' vision when navigating remote spatial areas. More recently, the work of Herbst et al. [98] attempted to apply temporal aspects by visualizing historical shades of objects at certain locations, as a simple way of allowing users to travel in time. However, the work described in their report [98] only supports temporal-based navigation in historical contexts with limited interaction capabilities. Thus, the user has benefits from time travel, but is essentially a passive observer of events as opposed to actively interact with the surrounding space.

Questioning Practices of Temporal Design

Current time design typically assumes a passive approach in which the system waits for the user to drive the interaction. This analogy is similar to passive learning approaches where learners await the teacher to instill knowledge. Interaction in such contexts renders systems as inactive and isolated from time when the user stops using them [100]. Huang and Stolterman [101] wonder "*do designers follow that approach intentionally, or is it because they did not reflect on possible integration of time in the design?*" We argue that the aforementioned approach is due to poor integration of time (as a learning aid) in the design, so we aim through our research to partially answer this question.

Lundgren and Hultberg [139] wondered if time can be explicitly used as a design element. For instance, how a program can be affected by time? How this affects use and design? They proposed temporal themes as a way to inform or change interaction, and that the visible temporal effects, in one hand, make it easy to working with an application and, on the other, are connected. In addition, Lundgren [138] highlighted the importance of exploring temporal behaviors in interactive artifacts to add functional components or new change the interactions. He argued that although not all artifacts should have temporality, it is important to question time design in the system.

Cooper et al. [37] expressed: "*However, first and foremost, interaction design focuses on something traditional design disciplines do not often explore: the design of behaviour that is inherently temporal.*" However, not enough integration of temporal aspects of interaction is considered in design, which negatively affects both the practice and research of interaction design [139]. Along the same line, the famous designer guru J.C. Jones [110] claimed that "*The traditional design method* *depends almost completely upon accurate modeling of dimension in space. The time dimension ... is left to take care of itself*". He added "*designers need to acknowledge their relative ignorance of 'temporal design' and can perhaps learn from the 'time art' (music, film, novel, etc) how to compose-in-time with some sense of beauty*". Following these insights, we argue that designers generally follow a linear timeline storytelling approach to the design of interaction flow in their interfaces. While efficient, this approach sometimes fails to exploit the broader complex, rich, and often non-linear nature of time, in addition to its interrelationships with spatiality. We attempt in our research to answer the aforementioned reflections by exploring intuitive ways of incorporating temporospatial elements as learning aids in the design of interactive systems, in order to enrich learners and enable quality experience.

2.7.3 Repetitive Learning

The role of failure in education is crucial as many people learn by experimenting, failing, and re-attempting until they succeed. In this part, we focus on existing research that aimed at supporting user's reflection and repetitive learning, and we give particular emphasis to the design and usage of interaction hitory as an important temporospatial learning aid.

Interaction History

Many systems today provide support for interaction history by allowing users to roll back and re-try things if the interaction did not work out as expected the first time (e.g., [156]). The design of such learning aids and tools have been under research for a while, ranging from supporting basic undo/redo operations, to visualization tools that enable complex nonlinear iterative form of interactions. An excellent survey, by Heer et al. have focused on the myriad history tools for supporting analysis, evaluation and communication [95]. The authors presented a design space analysis of interaction histories including the different ways of generating and capturing such interaction histories to visualizing and manipulating them. Our work, in part, focuses on improving interaction history nonlinear representations for spatial tasks following Heer's design space.

Logging interaction history generally requires actions or state modeling. In the first approach, user actions are modeled as commands that follow the Command design pattern [231] and can be applied or inversed as needed. The second approach utilizes application (or object) state that can be saved or restored as needed.

Typically, actions are captured in a simple (linear) representation [95] such as a stack (or list) of history items allowing the user to undo/redo his or her actions, as needed, or nonlinearly as branching structures including trees and graphs. For example, an image editing application may save and organize previous user actions either in a list, or in a tree structure reflecting the image edits as nodes in the tree representation.

Linear history models such as the undo/redo approach are common for their simplicity, but have specific limitations. Such models seem less suitable for 3D spatial contexts and therefore have been poorly explored in immersive enviornments. Also, the linear models oftentimes fail to preserve subsequent user actions after performing an undo. For example, if a user performed an undo operation after 10 steps and decided to return to the sixth step, the subsequent steps (from 7 to 10) are not preserved and the users loses that part of the history. In an attempt to stay away from the seemingly complex nonlinear approaches, existing research have attempted to mitigate this issue through The Selective Undo technique [14], which allows users to select and undo only specific operations from the past. Indeed, this technique has been successfully explored in various applications (e.g., [163]). Another approach by Nancel and Cockburn [165] was proposed as a model to clarify possibilities for temporal interactions following the concept of causality enabling applications to combine both the linear and branching approaches. This research, in part, focuses on the nonlinear approach with spatial tasks and attempts to highlight its potential for improving users' awareness of their interaction history.

Nonlinear history models and branching timelines (e.g., Figure 2.1) have the potential to preserve different user interaction trajectories over time. On one hand, most of these models are not popular because they are often abstract (e.g., [173] and [192]), utilizing simple encoding of user actions using text [111] or static image thumbnails (e.g. [32]), and because they require dedicated screen space for their graph/tree representation. On the other hand, few nonlinear branching models are gaining more popularity [50] and most of such applications are with simple, non-spatial tasks. For instance, image editing applications where a desired image effect can be achieved in different ways, and text editing scenarios that involve multiple users such as the well-known version control systems. We are only aware of one application of nonlinear history models, which is within the gaming industry. For example, Final Fantasy XIII-2 [64] featured, "Gate Matrix", a tree-like visualization that allows the player to jump between different times at the same location or different places at the same time, thus the player follows a branching path to access the different places instead of accessing them linearly. Another game, Tom Clancy's The Division, features Echoes as spatially superimposed 3D holograms of previous actions allowing the player to revisit the past while at certain locations [228]. Also, more recently an interesting research focused on enhancing immersive training by relating memory models to system and representation fidelity [143].

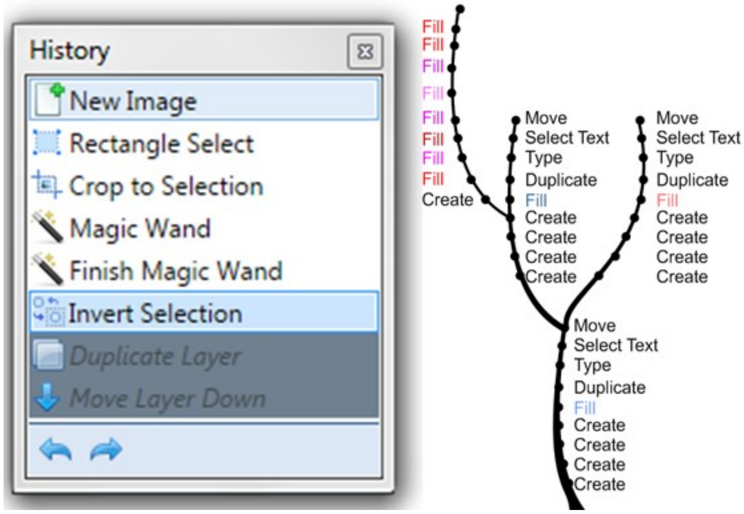

Figure 2.1: An example of capturing image edits in a linear history list (left), or in a nonlinear branching tree (right)

Logged history can also be logged locally (for each individual application object) or globally (for all application objects). For instance, an image editing application that enables working with multiple images at the same time may log the user interaction history per image or across all images. The visualization of each logged history item, whether in a list or a tree structure, utilizes descriptive text, an image thumbnail, or both. A web browser may utilize descriptive text for the titles of web pages that have been recently visited [111]. Other research and systems have explored representing each history item as an image thumbnail (e.g., [32]).

To our knowledge, most visualization of interaction history items lack effective visual encoding. While this can be sufficient for simple tasks, we argue that the flexibility of such nonlinear models deserve further exploration especially within immersive spatial environments. Therefore, we focus on exploring nonlinear interaction history representations in spatial tasks and argue that having improved representations would increase users' awareness and control of their interaction history (as demonstrated in Chapter 5).

Chapter 3

Rethinking Learning Aids in Immersive Environments

In this chapter, we present a framework focused on exploring learning aids in immersive environments. We begin by reviewing key theoretical learning models. We then reflect on how technology and technical advances contribute toward effective design of learning systems. Finally, we outline our learner-centric approach utilizing learning aids with concrete examples of how these aids have the potential to enable quality learning experiences.

3.1 Introduction to Learning

There are many definitions of 'learning' although people may intuitively have an understanding of it [6]. To set the context, we begin by presenting some of these definitions.

One definition defines learning as a process where the learner 'take in' ideas, with the representation/expression of that learning is the manner in which the quality or quantity of the learning is evidenced [150]. In another definition, it is a process that brings together personal and environmental experiences and influences for acquiring, enriching or modifying one's knowledge, skills, values, attitudes, behavior and world views [229]. From our point of view, learning could mean to expand learners' knowledge of the world and to gain new skills. Here, a skill is a form of representation of learning and it is the ability to do something that has been learnt.

3.1.1 Different Views of Learning

In general, learning can be viewed in two ways. This first one is (passive) instruction-based learning, in which the learner acts as an information collector, absorbing material taught and retaining it. In this passive view, the teacher provides for the learner the bricks of knowledge and it is assumed that the teacher knows how these bricks fit together. However, this view is limited as it requires having an instructor and ignores how people learn in a vast majority of everyday situations [123].

In the second view, learning takes a more active form with important development beyond the notion of 'accumulation' by which the context and experience guide what we choose to pay attention to, what we choose to learn, and how we make meanings of the material of learning (i.e., conception of knowledge).

3.1.2 Learning Theories

In this section, we review key learning theories and how researchers from different fields have attempted to explain learning. We begin by defining what we mean by a theory. In simple terms, a theory is a way of thinking and a model of how things work, how principles are related, and what causes things to work together. It may also be defined as a simple representation of more complex forms, processes, and functions of physical phenomena. It is a visual representation that helps people conceptualize reality and explains methods that are used to achieve a goal [88]. In our context, learning theories address the following key questions: how does the learning process take place? how knowledge is absorbed?, and how do cognitive, emotional and environmental factors affect learning? In an attempt to answer these questions, our review focuses on theories from the fields of psychology and philosophy, as detailed in the following sub-sections.

Psychology of Education

The field of psychology is prominent for its efforts on understanding how we learn. In this regard, Edward Thorndike, a well-known psychology researcher is considered one of the first and key behavior scientists who attempted to explain learning [224]. According to Thorndike, the process of learning is incremental with learners acting as collectors of information. He hypothesized that the environment should to be structured with certain stimuli that would 'produce' learning. In other words, Thorndike put forward a "Law of effect", which stated that any behavior that is followed by pleasant consequences is likely to be repeated, whereas any behavior followed by unpleasant consequences is likely to be stopped. In essence, the field of behvior analysis views the learning process as a change in behaviour where the environment is adjusted to elicit desired responses (learning outcomes) and with the stimuli followed by a relevant effect (positive or negative reward). The application of this theory can be helpful for certain types of skills especially those that can be learned mindlessly and repeatedly through reinforcement and practice. However, its effectiveness may not be established for tasks that require higher mental complex processes where people need to make sense of what they are experiencing.

Contrary to the behaviorist approach that was criticized for being too dependent on behavior to explain learning, gestalt psychologists propose looking at patterns rather than isolated events. They claimed that we do not obtain knowledge from what's in front of us, but rather we often learn by attempting to make sense of the relationship between what's new and old [6]. One challenge that can arise with this view of learning is when learners face new material that may conflict with their beliefs or views of the world. Further efforts building on Gestalt psychology were framed as cognitive theories aiming to explain the way we organize our sensations into perceptions [6]. According to these theories, people receive information and process it with cognitive operations before storing it in their memories. Therefore, two assumptions are important for learning with this approach: a memory system as an active organized processor of information and the existence of prior knowledge. This model contrasts with the previous understanding of learning as collection of responses to external stimuli, as understood by behaviorists. Generally speaking, instruction methods that follow the cognitive model tend to prefer lecturing and reading textbooks, and assumes the learner as a passive recipient of knowledge by the teacher.

In summary, early theories about psychology of education viewed learning as a passive process. According to these theories, learners receive information and keep it in their memories and sometimes this happens in response to specific stimuli. Still, the ideas mentioned in these theories provide insight into the importance of motivating learners and carefully representing the learning material to achieve specific outcomes. Our learner-centred approach takes inspiration from these ideas and proposes new educational aids to facilitate learning as discussed later in section 3.2.

Philosophy of Education

In philosophy, researchers have attempted not only to explain how learning takes place, but also have discussed the importance of education in our life, the role and shape of educational institutions, and the social impact on learning.

The nature of learning was first described through constructivism, which emphasizes the importance of active involvement of learners in constructing knowledge for themselves [109]. One of the key prominent theorists of this view is Jean Piaget who focused on how humans make meaning in relation to the interaction between their experiences and their ideas [235]. It was argued that learners not only receive information (in a passive way), but they also actively construct their knowledge in interaction with the environment and through the reorganization of their mental structures. In other words, learners became sense-makers who interpret information after receiving it. Thus, the metaphor of learning moved from "knowledge-acquisition" to "knowledge-construction." This view reflects on the importance of interaction in the design of learning environments, which we detail later in our discussion about learning aids 3.3.

The constructivist view of learning is essentially a learner-centred approach whereby the teacher guides learning and is not merely a knowledge transmitter. In this regard, the design of effective learning systems could benefit from different versions of the constructivist approach including discovery-based learning [27] and active learning [19]. It is worth noting that while such approaches provide opportunities to enhance learning through discovery, motivation and knowledge construction, research has also shown that blindly adopting such approaches may have detrimental effect on other learners, especially novices or those with little prior knowledge (e.g., [121]). In this regard, the concepts of flow and learning styles, as discussed later in section 3.2, would be of particular importance for supporting active learning.

Philosophers of education have also discussed the importance of context for learning. In this regard, the pioneer work of Vygotsky criticized the information-processing constructivism view of learning as processes occurring within the mind in isolation from the environments and interactions with their surroundings [234]. This has led to the introduction of “situated learning” by Lave that emphasized the significant role of context and social interactions [127]. In the new view, interactions between individuals and situations contribute to learning; knowledge is considered as situated and is a product of the activity, context and culture in which it is formed and utilized. We also acknowledge the importance of authentic contexts for learning, and encourage designers to consider this important aspect when designing effective learning environments (Refer to section 3.3 for details).

Social Aspects of Education: we review the work of John Dewey as a prominent philosopher, psychologist, and educational reformer. Dewey has discussed key relevant ideas including the importance of education in our life, the role and shape of educational institutions, and the social impact on learning.

The ideas of John Dewey have been influential in education and social reform. Dewey repeatedly highlights the importance of education not only as a place to gain knowledge, but also as a place to learn how to live [53]. According to Dewey, education has a purpose beyond the acquisition of skills towards the realization of one’s full potential and the ability to use those skills for the greater good. In addition, Dewey considers education and schooling as instruments for creating social change and reform. Dewey also believed that all learners should have the opportunity to take part in their own learning, and that they should be allowed to experience and interact with the curriculum within the learning environment.

With this important view that considers both learners and the learning environment, Dewey calls for a balanced educational structure that supports knowledge delivery while also taking into account the interests and experiences of learners. For this reason, the ideas of Dewey were considered an important source of inspiration for experiential learning [52]. In Dewey’s view, for an experience to be educational, certain parameters had to be met, the most important of which is that the experience has continuity and interaction. This is very similar to the concept of flow where the continuity of the experience comes from and leads to other experiences, encouraging the person to learn more.

3.2 Towards Effective Learning

In this section, we outline and discuss key factors that impact and contribute to effective learning. We begin by defining active learning. We then focus on the role of experience, technology, and authentic environments on learning. We also highlight the importance of emotion, scaffolding, and having multiple representations of educational material on learning outcomes and the overall user experience.

3.2.1 Active Learning

In active learning, learners actively participate in the process instead of being merely spectators receiving information. Principles of active learning include relevancy of the task to learners' concerns, reflection on the meaning of what is learned, and dependency on situation in order to establish learning tasks. To demonstrate the value of active learning, consider when someone knowledgeable is teaching and supervising another on how to cook a new dish. In this example, the supervisor is not merely providing instructions but also engaging with the learner, allowing him or her to try things and providing feedback as needed. This may be known as the apprenticeship model [35]. Indeed, this active approach can be valuable especially with the availability of qualified mentors. However, it may fail in certain scenarios when mentors are limited, busy, or when there is a need to match learners and mentors based on their skill sets. To mitigate the dilemma of either having passive or active learning, we argue for innovative use of interactive technology, including humanoids as instructors or immersive simulation that would individualized learning, as a middle solution reflecting a semi-active learning approach 3.3.

3.2.2 Learning and Experience

In this section, we begin by reviewing the role of experience in learning. We then focus on the experiential learning approach and some of its applications.

We learn (something) in relation to our present and prior experiences since the prior experience guides how we respond to a present one. Therefore, learning is about meaningful experiences in everyday life that lead to a change in an individual's knowledge and behaviors. Carl Rogers is an influential proponent of these theories, suggesting that experiential learning is "self-initiated learning" as people have a natural inclination to learn; and that they learn when they are fully involved in the learning process [194].

Another way to understand the relation between learning and experience is by understanding that our experiences can be internal and/or external. The former represents the material of learning when we learn about something outside of ourselves. It is the object, idea, concept, image - whatever the learners want to assimilate. In contrast, the latter, internal, experience is what learners bring to the learning situation from their current cognitive structure.

Beginning in the 1970s, David A. Kolb helped to develop the modern theory of experiential learning, building on social and constructivist theories of learning and drawing heavily on the work of John Dewey and Jean Piaget [123]. The Kolb approach to experiential learning is achieved through a cycle of concrete experience, reflective observation, abstract conceptualization and active experimentation (Figure 3.1).

Learning is not about content knowledge anymore. The experiential learning model situates experience at the core of the learning process, and aims to understand the manner in which experiences whether first or second hand motivate learners and promote their learning. Experiential learning is designed to improve people understanding by giving them the freedom to explore and find the learning path that is most suitable for them. It is about immersive experiences wherein learners can figure out where to go, what questions to ask, how to collaborate and contribute. Learners would see mistakes as growth opportunities, not as a failure of their abilities.

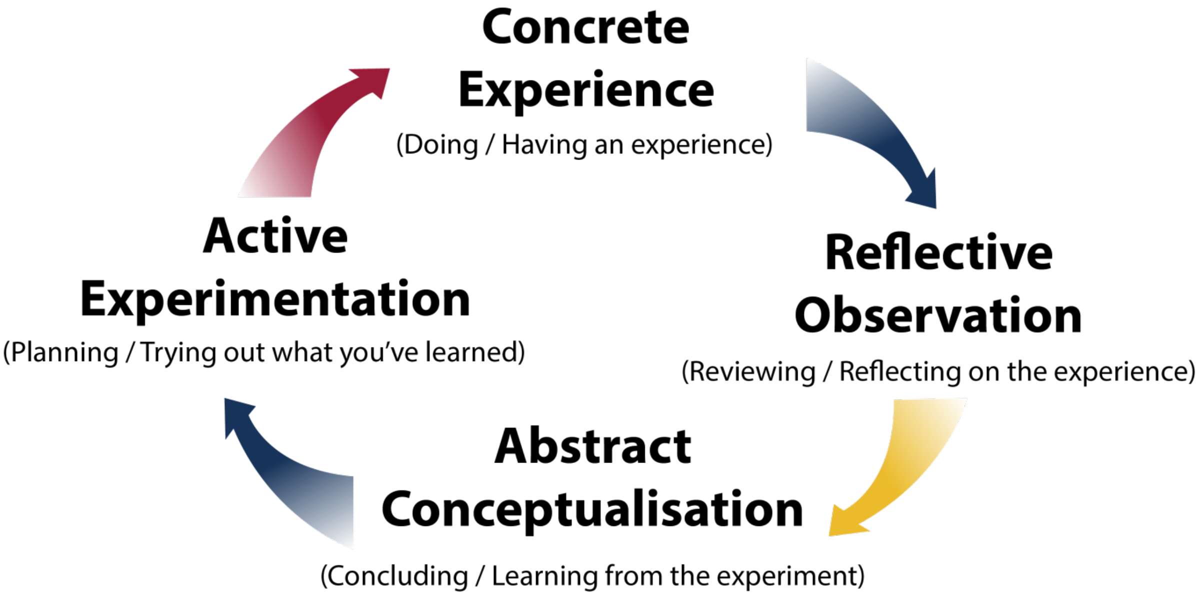

Figure 3.1: Experiential learning cycle.

Various researchers have attempted to utilize the experiential approach in their explorations. Games have studied the experiential model and its suitability in immersive learning environments (e.g., [116]). Similarly, the experiential learning cycle has commonly been utilized as a theoretical basis for simulation-based education [47].

In this research, we utilize our understanding of experiential learning to facilitate how users learn about or train specific tasks in practical immersive environments. In particular, we explore how to engage learners and support them with reflective capabilities to achieve best learning.

3.2.3 The Role of Technology

With all the technology available today, there is growing interest in technology-rich learning environments. This is especially true for simulation-based education in various practical fields such as aviation and surgery. In this section, we review some of the key works on applications of technology for learning. After that, we discuss ideas that relate to the design of educational technology.

Researchers have attempted to discuss the impact of technology and how they leverage theoretical education models to optimize learning experiences. For example, the early work by Hannafin and Land [92] revised and critically analyzed research and theory related to technology-enhanced student-centered learning environments and identified key foundations and assumptions. In another work [233], the authors discussed theoretical and design principles for building effective learning environments using recent technologies such as mixed reality, video games and simulations. More recently, Lombardi [135] explored what constitutes authentic learning, highlighting why it is important and how technology supports it.

In general, the design of interactive educational technology should utilize available multisensory channels including at least both the visual and auditory channels for information processing. Good examples are games and simulations with their potential to engage, train and educate. Such systems can be particularly effective for learning skills and attitudes that are not so easy to learn by rote memorization. Similarly, exploratory-based contexts where learners can and are encouraged to discover new knowledge reflect a high quality interactive learning. In this regard, the design of systems should motivate and enable learners to explore, adapt to their skills, and provide guidance as needed.

3.2.4 Learning in Authentic Contexts

We agree with theoretical and practical research that call for situated contextual and authentic learning environments (e.g., [234] and [127]). Indeed, such contexts should replicate valid scenarios embedded in authentic tasks and activities, reflecting the kinds of situations that learners would face in the real world. These environments should also be designed to help learners develop knowledge that is useful and flexible, not inert, by providing realistic problems that do not necessarily have “right” answers [45].

3.2.5 Transfer of Learning

A key idea behind learning is that what one learns in one context should carry over to another (i.e., knowledge transfer). The notion was originally introduced as transfer of practice by Edward Thorndike and Robert S. Woodworth [247]. They explored how individuals would transfer learning in one context to another similar context. Today, the transfer of learning is usually described as the process and the effective extent to which past experiences affect learning and performance in a new situation [63]. The transfer of knowledge goes far beyond simply repeating memorized material to being able to take old knowledge and experiences and apply them to a new concept or to solve a problem that has never been encountered before.

Current learning approaches that focus on conveying knowledge may fail to support transfer of learning. Early research on educational psychology [5] claimed that the reason for such failure may be because learning happens independent of the context within which it gives meaning. Therefore, engaging methods utilizing technology such as simulation and games have potential to facilitate transfer of learning. This is especially the case when these systems are properly designed to encourage reflexive learning by replicating the context and allowing learners to reflect on past experiences. Here, we argue that factors that could support transfer of learning may include features of the task (e.g. simulation, problem-based learning, authentic immersive tasks, and good presentations that promote visual thinking) and features of the learners (e.g., their ability to reflect on past experiences, to practice skills, and to participate in discussions). In this research, we aim to maximize transfer of learning by re-visiting educational aids that mediate experiential learning in immersive environments.

3.2.6 Adaptive Learning

Thorndike highlights that the nature of the learning process is incremental [224]. He called for supporting adaptive gradual learning that mimics how children learn step-by-step and how we adapt to their progress. Building on that, we argue that one of the effective learning strategies is to carefully adapt to learners' styles and individual differences.

Learning Styles and Learners' Needs: The argument here is that we should build on outcomes of learning style theories by attempting to optimize for each learner's preferred style and needs to ensure faster and more satisfactory improvement [75]. Along the same line, all students should have equal learning opportunities. Unfortunately, this is not always the case. Consider for example a classroom scenario, in which we do not expect that all students are learning the same material fully. This is particularly true when different students are given different grades. However, experimental studies show that almost everybody learns in a one-to-one environment. Accordingly, the argument is that the learning environment is the issue and not the student. It is not feasible, however, to focus on one-to-one learning for potential learners due to cost and lack of skilled teachers. Ideally, we should have a variety of learning strategies (e.g., using different media and pedagogical directions) to ensure suitability to each individual, and in the optimal case learning should be individually paced. We argue that simulation and experiential immersive systems have the potential be mediate learning and by adapting to learners' styles and needs 3.3.

Gradual Learning and Scaffolding: Scaffolding facilitates adaptive learning. It is an educational concept by Lev Vygotsky building on the idea of "Zone of Proximal Development". In this concept, learners are given a lot of guidance when they start learning and this guidance is minimized based on the learners' adaptation and/or skill improvement [31]. In other words, scaffolding is the process of controlling the task elements that are initially beyond the learners' capacities. So, the learners can focus on the parts within their immediate capacities and then led to other aspects of the task that build upon the previous.

3.2.7 Emotions Affect Learning

Learning should be interesting and enjoyable to students. Ideally, the learning process is meant to be a life-long activity learners engage in and this will only happen if they find it a pleasant one. Conversely, learners who are fearful, anxious, depressed, or distracted cannot focus on processing new information. Therefore, emotion plays a critical role in affecting both learning and learners. In this part, we discuss the key aspects that relate to emotion and learning: motivation, immersion, flow, and gamification.

Motivation: Motivation is a key concept in captivating learners and keeping them engaged. Generally, it consists of two types, intrinsic and extrinsic. The former is when people do the activity for its own sake and enjoyment without waiting for or expecting any reward. The latter, is a behavior when people seek to obtain some reward or avoid punishment. Motivational models usually involve both behaviors.

A set of four design principles for promoting intrinsic motivation in instructional activities was proposed by Mark Lepper [38]. The first is giving learners a sense of "control" over the activity. The second is to have continuous "challenge" with gradual difficulty and uncertain attainment. The third appeals to the sense of "curiosity" by hinting at areas of inconsistency, and the fourth is of utilize the activity in a functional simulation or "context."

Immersion: The learning materials and how they are presented greatly affect the educational experience. In general, when learners are engaged within an immersive environment, they often experience a more empowering form of learning than through typical text or video-based materials. The utilization of immersion in learning aligns with the experiential approach. Thus, it has the potential to improve transfer of learning by allowing users of simulation and virtual environments to practice what they are learning in a safe, semi-realistic, and affordable environment. This insight is in line with existing research on the impact of immersion on learning environments (for more details, we suggest reviewing this section 2.6).

Flow: Flow has been heavily researched in psychology, games and the design of digital experiences [41] and [117]. Flow may be understood as a state with full mental involvement and continual engagement with an activity. It is the ideal state between boredom and frustration, and it can be regarded as an important goal of designing immersive environments.

Flow is often experienced when the design strikes a balance between users' skills and the designed task challenges. Flow may seem to encompass both *Motivation* and *Immersion*, but it also involves adaptation to learners' skills and having seamless interaction. In this regard, Csikszentmihlayi [41] identified eight aspects for making flow possible: An achievable task (that seems difficult but doable with some effort), Concentration (hinting at having little distractions and aiming for focus), Clear goals (of what to be accomplished), Feedback (that is immediate and continual), Effortless involvement (by the users), Control over actions (that have immediate and purposeful results), Concern for self disappears (the users are fully immersed), and Losing the sense of time (through an engaging experience).

Gamification: In our modern day, electronic games and simulation have begun to enter contemporary formal education. Gros [87] has examined the evolution of games in education including the challenges involved in the use of games for learning.

Games and simulation provide rich mediums that inspire and help the creation of effective learning environments. Indeed, the active approach of gamifying educational systems could benefit creativity and support learning transfer [54]. Games could also augment learners' problem solving skills and help to improve learners' visual, motor and intellectual skills [46]. Gamifying learning might also be one possible approach to reducing cognitive stress in terms of task complexity and difficulty. We argue that important elements inspired from games and simulation such as motivation, narration, fun, challenge, immersion, and multisensory cues can be regarded as educational aids that improve the overall learning experience. According to Pransky [185], games enable and support learning techniques including active participation, practice and feedback, learning by doing, learning from mistakes, goal-oriented learning, task-based learning, discovery learning, question-based learning, situated learning, and role-playing learning. For a detailed discussion on how games and simulation have the potential to improve learning, we suggest reviewing the section on gamified education 2.5.

3.2.8 Representation of Learning Material

In most cases, when learners encounter only one model, one analogy, or one way of understanding complex content, they often oversimplify as they try to apply that one approach to every situation. Therefore, multiple representations of the learning content is essential to help learners be aware of different ways of how they may do something. Furthermore, by designing the learning content with suitable visual encoding and with combination of multisensory cues, it can positively impact learning. This is in line with how information visualization research helps cognition and enables exploration and discovery [239].

In general, people learn by making sense of the environment and of stimuli around them. Greater perceptual development and learning occur in environments that are rich with stimuli and provide useful feedback in response to learners' efforts to act upon the environment. This argument is supported by early theoretical work highlighting how stimuli and feedback support learning [224]. In this regard, the nature of the task that is confronted, the ways in which information is presented, and the expectations for the learners' involvement all impact the learning process.

3.3 Learning Aids in Interactive Immersive Environments

Learning through immersive environments and simulation has been recognized as being complementary to hands-on experience. However, one of the ongoing challenges to wide adoption is the capacity of such tools to incorporate educational features required into their design from inception rather than as an afterthought to ensure effective learning. In this section, we identify key challenges facing learners in these environments. We also propose re-visiting educational aids to mediate experiential learning in interactive immersive environments.

In general, immersive virtual learning environments are designed to be domain specific simulating practical scenarios (e.g., [186] and [118]). These environments are gaining more popularity and increased usability. However, we argue that most systems would still benefit from re-visitation of educational aids to facilitate the overall learning experience [12]. In particular, learners could be supported by simplifying one or more of the following difficulties, which would contribute towards effective and experiential learning:

1. Lack of innovative guidance such as on-demand dynamic hints or temporal trajectories. Instead, many systems support guidance through limited tooltips and assume that users should consult the associated documentation.
2. Complex interface and complicated interactions sometimes involving the need to coordinate between multiple devices. Such complexity often reflects a steep learn-

ing curve and leads to poor usability that discourages many users.

3. Ignoring experiential aspects such as situated learning, engagement, and immersion. Learners ideally learn within authentic environments as detailed earlier (section 3.2.4) and ignoring this aspect in the design could negatively impact the overall learning experience.

4. Lack of proper performance reporting and reflective feedback. This usually impacts learners as they will not learn from their own mistakes and hinders repetitive learning.

5. Limited availability of skilled instructors. This difficulty may slow down the overall learning process.

6. Cost, as learners cannot afford to have their own simulations. Arguably, learning through textbooks and technological-based content is available, but simulation-based approaches are expensive and only exist in specific learning contexts such as university labs. There is still a need to simplify the cost of immersive learning systems to make them affordable for typical users at home.

7. Poor visual representation of the learning content. This is often intensified with limited control over how the learning material is presented since many of current systems are built with a one size fits all approach.

To mitigate the aforementioned issues, which we identified based on our personal observation and by studying existing learning systems (e.g., [136] and [249]), we call for a learner-centred design approach. Here, we take inspiration from learning theories and re-explore existing educational aids and propose new ones such as guidance trajectories reflective interaction features to mediate experiential learning in interactive immersive environments. We encourage designers to consider one or more of the following learning aids.

3.3.1 Simplified Interactivity

Design simplified interface and interaction capabilities especially for novice users. This common usability suggestion is more valid for learning to ensure lower cognitive load.

3.3.2 Memory Empowerment

A novel approach inspired from learning theory is to empower learners' memory and promote deliberate repetitive practice. For instance, users need to be aware of their interaction history to reflect and better learn from their own mistakes.

3.3.3 Individualized Independent Learning

This novel aid calls for a smooth learning curve where learners are able to learn in an individualized independent manner. In other words, experiential learning systems should be designed allowing learners to independently learn and gain knowledge even with the absence of mentors or instructors.

3.3.4 Contextualization of Learning

A situated environment is essential for experiential learning. The design of effective context should encourage motivation and engagement for better learning. Also, targeting immersion and multi-sensory elements should be considered, whenever possible because of their potential to mediate experiential interaction.

3.3.5 Humanoid-based Instructors

With the lack of skilled instructors, a novel approach that can be suitable and beneficial is to consider technology-based teachers (e.g., humanoid). Such smart robots can successfully assume the role of instructors for many educational tasks.

3.3.6 Effective Content Representation

It is important to carefully represent the learning material as suggested by theory and practice. In addition, it can be valuable to provide flexible representation of learning content that adapts to learner's prior knowledge and progress over time.

3.3.7 Feedback and Performance Measures

It is not enough to provide basic feedback during user's interaction. Especially for learning, it is more important to integrate detailed performance measures and feedback through the whole learning process and especially at the end of it.

3.3.8 Appropriate Tool Fidelity

Building a learning environment may involve custom tools and devices that may be expensive or hard to get. Simulation attempts to simplify this issue but careful consideration of fidelity is important. In essence, we encourage designers to build with fewer tools and target affordable low-cost gadgets for learning whenever possible. For instance, when building an immersive environment that involves haptics, consider different types of haptic devices and target affordable ones that provide reasonable fidelity.

3.3.9 Temporospatial Elements

Temporospatial elements represent a set of proposed concepts that relate to space & time and can be utilized in design to enrich interaction within 3D contexts [157]. We regard many of our learning aids as temporospatial elements that could augment users' interactions and the overall experience. Examples of such elements include providing users with guidance trajectories, hinting at important changes to objects, and allowing users to repeatedly train the task at hand.

Our exploration of the temporospatial elements might envision learners as superhumans with unique abilities where they can manipulate space and/or time to achieve their goals. For more information about the concept of superhumans in immersive environments, refer to Appendix 2 B.

3.4 Examples of Learning Aids Scenarios

In this section, we demonstrate the potential of exploring learning aids in everyday immersive contexts. Through the following scenarios, we highlight how such aids can be utilized to enrich interaction and the overall experience.

3.4.1 Cooking

Consider an immersive system for learning how to cook. During the cooking task, users need to pour water quickly over a mixture of ingredients. The system may utilize the temporospatial and learning element of "trajectory" to guide the users about potential interaction possibilities (e.g., hint at the next ingredient to be added as shown in the bottom of Figure 3.2). The trajectory of interaction can be further enriched when combined with the temporospatial learning element of "velocity", encouraging the users to perform this action quickly, e.g., by animating the dotted trajectory that links between a water jug and a container with the mixture. Here, the dots in the trajectory are visualized with movement speed, reflecting how quickly the users should perform the task. Without such temporospatial augmentation and learning aids, the users may not interact quickly enough and the cooking ingredients would become spoiled, leading to a failed educational experience.

This illustrative cooking scenario may also involve the integration of unique reflective features within its spatial representation for improved learning. In this regard, the cooking context may be organized into sub-spaces reflecting particular time connotations. For instance, the cooking sub-space to the users' right may reflect an area where the simulation is presenting possible future implications of different actions (some for example presenting the ready dish, or a burned version of it), or wherein the simulation rate is moving faster than the normal rate (e.g., items therein would cool quickly).

Similarly, the cooking sub-space to the users' left may represent a storage of past actions performed by the users, which we have termed "ReflectiveHUD", a representation that serves to pro-

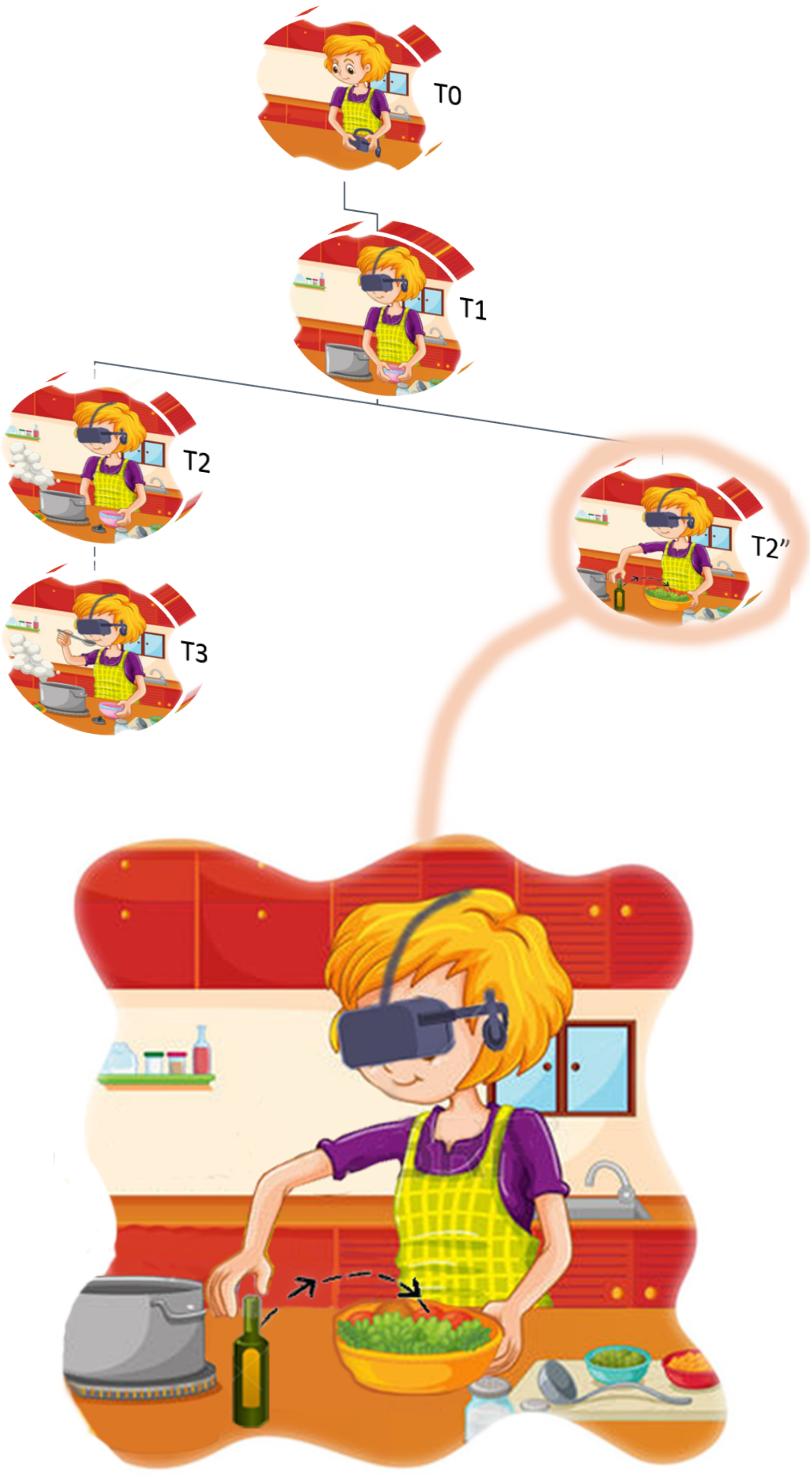

Figure 3.2: Bottom: An animated trajectory hints the user at the need to add the content of the bottle to the ingredient mixture, Top: shows an example of the sequence of interactions and with the ReflectiveHUD tree nodes reflecting key interaction moments.

vide users with the ability to control their interaction history; navigate back and forth in time to a particular moment and to try different actions (Figure 3.2 Top). Also, the left area may be utilized to simulate different temporal rates (e.g., objects therein would heat quickly) through vertical subdivision. For example, items in the top-left area can heat much faster (e.g., using simulation rate t1) while items on the bottom-left area can heat a bit slower (e.g., using simulation rate t2). In this regard, temporospatial elements such as "direction" and "scale" have been utilized, affording and providing more possibilities to the users when engaging within the 3D interactive context. In essence, the utilization of temporospatial learning aids in this example highlights a unique way of subdividing some of the spatial elements of the immersive environment based on temporality.

3.4.2 Immersive Entertainment

A virtual environment for dancing or creative painting could be another interesting everyday immersive example. We argue that the design of such illustrative applications would benefit from temporospatial learning aids. For instance, the trajectory of dancing can be visualized with an animation that guides users' movements in space over time; hinting at the sequence of the dance. Furthermore, users could try to dance from the perspective of other users ensuring continuity among users in such experiential environment. Also, designers may enable freezing time so that users can see the traces of their dance, and share it with friends.

Immersive painting similarly empowered by temporospatial learning elements may allow people to navigate and explore drawings from their interaction history. Figure 3.3 shows an example of immersive painting empowered with temporospatial learning aids.

3.4.3 Spatial Awareness and Reflective Room Interactions

To demonstrate how innovative learning aids can support reflection and spatial awareness, we imagine an everyday scenario where a user is about to enter an immersive office environment. The user may immediately see shadows of oneself at different potential locations inside the room as if she was interacting with certain objects. Examples of such shadows may reflect users' previous

Figure 3.3: Illustrative example of immersive painting with visual shadowing, as temporospatial learning aid, that guides user interaction.

interactions such as reading a book or a past representation of one user chatting with another person.

The transparency of the aforementioned temporospatial reflections (e.g., footsteps, volumetric shadows, or halos) may differ hinting at more valid, more recent interaction, past or future possible trajectories. Also, such reflections may be beneficial in exploratory learning where the user's prior experience enables a more active form of simulation. Here, the spatiality of the immersive environment enables rich interaction with time. Indeed, a very similar idea has been implemented in the gaming context of, Tom Clancy's The Division, featuring Echoes as spatially superimposed 3D holograms of previous actions allowing the player to reflect on past interactions while at certain locations (Figure 3.4)

3.4.4 Predictive Interaction with Oil Reservoirs

Consider a more practical example that could benefit from temporospatial learning aids. Here, we use an illustrative case study related to reservoir engineering (Refer to Appendix A.1 for a detailed background). In this example, we envision a simplified instance of how the visualization and (temporal) simulation of a reservoir model would change in relation to space. The user's

Figure 3.4: Visualization of holographic Echos reflecting past actions within the gaming environment of Tom Clancy's The Division.

goal in this task is to explore and learn about the reservoir dynamics and examine the correlation between static and dynamic properties. We use the following scenario to demonstrate a richer exploration of temporospatial learning elements and how they can enable experiential interaction and visualization of the reservoir representation.

At the beginning, standing in a tracked space (i.e., room), a user sees a typical floating visualization of a reservoir model directly in front of him (Figure 3.5). For interaction, the user can use gestures or carry a controller (e.g., Wii remote) to control and interact with the reservoir.

The virtual space is divided into various subdivisions through a representation that reflects each subdivision. Thus, each subdivision indicates a special (temporal) meaning/feature. Moreover, the system utilizes temporospatial significations to augment this representation, suggesting at what it means. In this example, the space is mainly subdivided horizontally into three subdivisions. The middle one, wherein the user initially stands, reflects a static visualization of the reservoir with no special signification (e.g., no simulation dynamics). The subspace to the user's left aims to emphasize the dynamic reservoir property of "pressure" with an animated visualization. The right subspace, similarly, aims at emphasizing the reservoir property of "saturation" with another

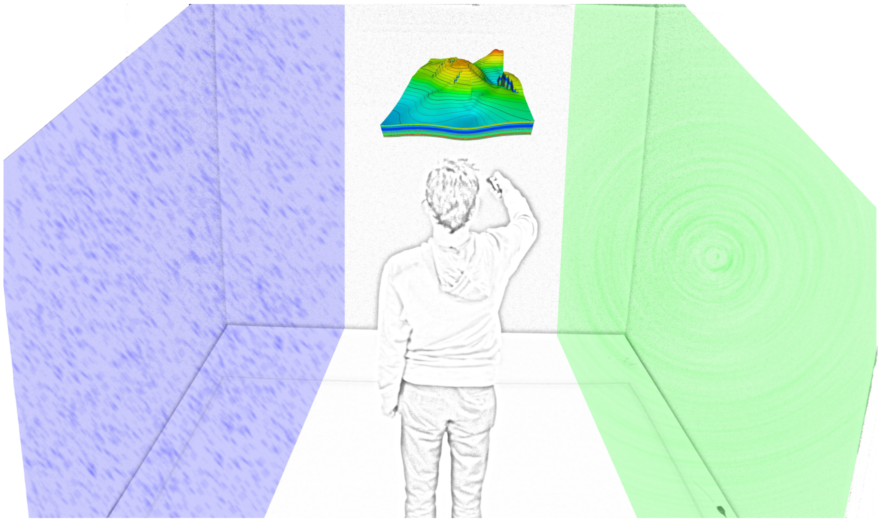

Figure 3.5: An expert user stands in a virtually subdivided space with a reservoir visualization floating in front

different coloring/animation. In addition to the horizontal subdivisions, vertical subdivisions can be utilized to reflect different rates, e.g., when running the simulation of the "saturation" property.

If the user decides to translate the visualized reservoir or its clone by moving it horizontally to the right subspace (Figure 3.6), the visualization of the reservoir model changes to reflect the simulation of the saturation property. Moreover, the user adjusts the vertical location, by cloning another representation of the reservoir so that the simulation rate is reduced.

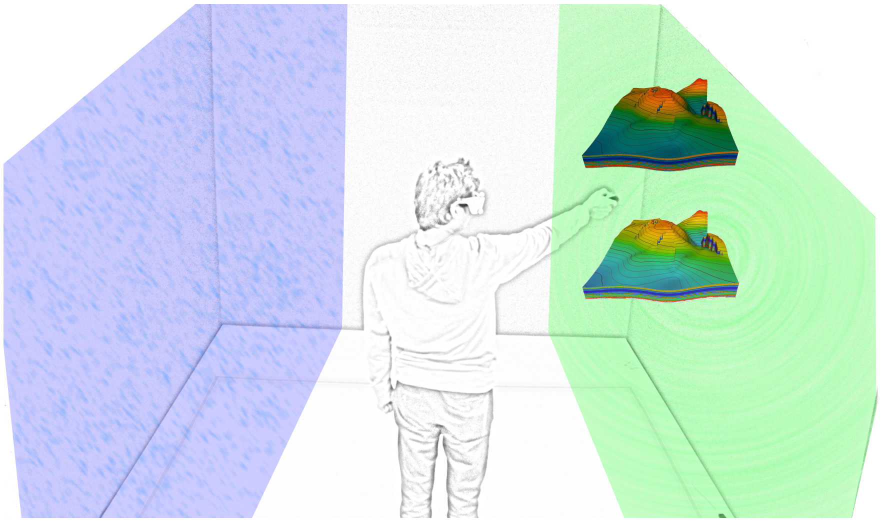

Figure 3.6: Moving the reservoir representation to the right starts the saturation simulation, where the vertical location reflects the rate of the simulation

The user also decides to clone the visualized reservoir and place the new clone on the left subspace (Figure 3.7). Accordingly, the reservoir representation reflects a transparent trail for all the time-steps (i.e., frames) of the simulated pressure property of the reservoir. The user can navigate the shown trail by dragging the air in this left space.

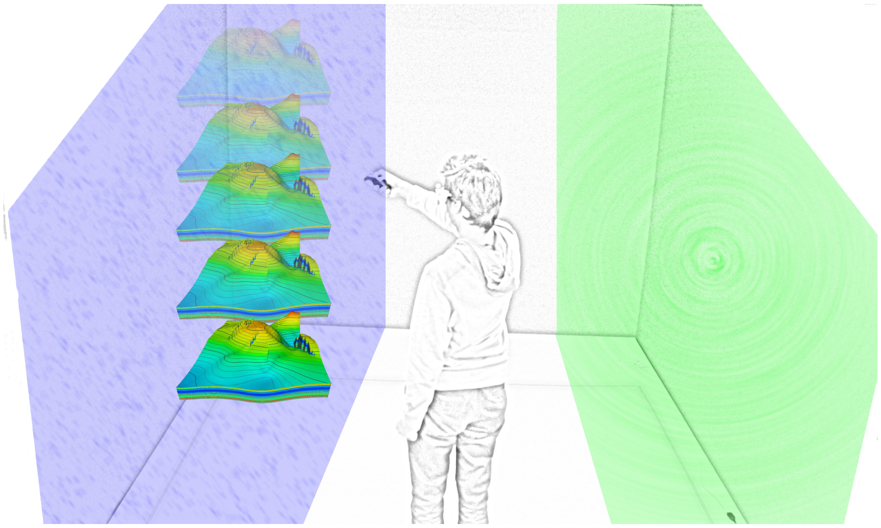

Figure 3.7: illustration of how the dynamic reservoir property of pressure is visualized as a transparent trail reflecting all the time-steps upon moving the reservoir visualization to the left

As shown in Figure 3.8, the environment depicts multiple representations floating in different spatial locations by the end of the interaction. In particular, the middle space is dedicated to showing various (non-temporal) visualizations of the reservoir (i.e., wireframe, open reservoir layer, filtered reservoir model, etc.). Both the left and the right subspaces reflect temporal explorations, emphasizing the simulation of the pressure and saturation properties, respectively. Such arrangements which were made simpler using temporospatial interactions provide an intuitive way of utilizing off-screen space by having multiple representations placed side-by-side for analysis and comparison. Without such temporospatial reflective exploration, the off-screen physical space (e.g., CAVE room) would be poorly utilized and additional user interface elements/controls may be required to explicitly change each representation.

In summary, we argue that the ability to view the task representation in different ways is valuable for learning. It also supports knowledge transfer where learners would be able to relate some

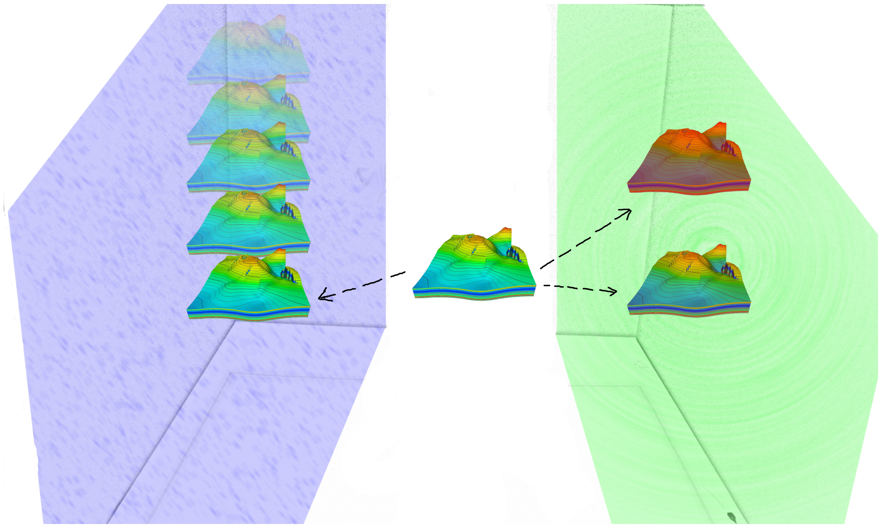

Figure 3.8: an illustration depicting the reservoir representations at the end of the interaction of the various representations to a real-world context.

3.4.5 Time Manipulation for Novice Trainees in Surgical Simulation

The example in this section utilizes the context of aneurysm treatment as detailed in Appendix A.2. It also builds on temporal distortion ideas inspired from psychology as discussed in Appendix C

In the example, we use Persona [37] to illustrate how time manipulation can be useful in supporting training within this surgical simulation scenario. Imagine Mark, a second year surgery resident who practices the treatment of clipping an aneurysm with a particular focus on honing his skills of awareness and critical decision making. Such skills can be particularly useful in the actual surgical task of aneurysm treatment especially when one or more complications arise [77]. For instance, it would be helpful to train how/when to react to handle the aneurysm's rupture or brain swelling. The context, in Figure 3.9, shows Mark about to interact with the virtual head of a patient on one table and a set of surgical tools on the other. This set of surgical tools includes medical scissors as well as medical clips that are particularly relevant to the treatment of an aneurysm.

Once the procedure starts, the system depicts an animation that automates and shows the initial medical steps that are less relevant to temporospatial exploration. This includes simulating the opening of the skull and moving aside brain tissue and vessels to expose the aneurysm. When

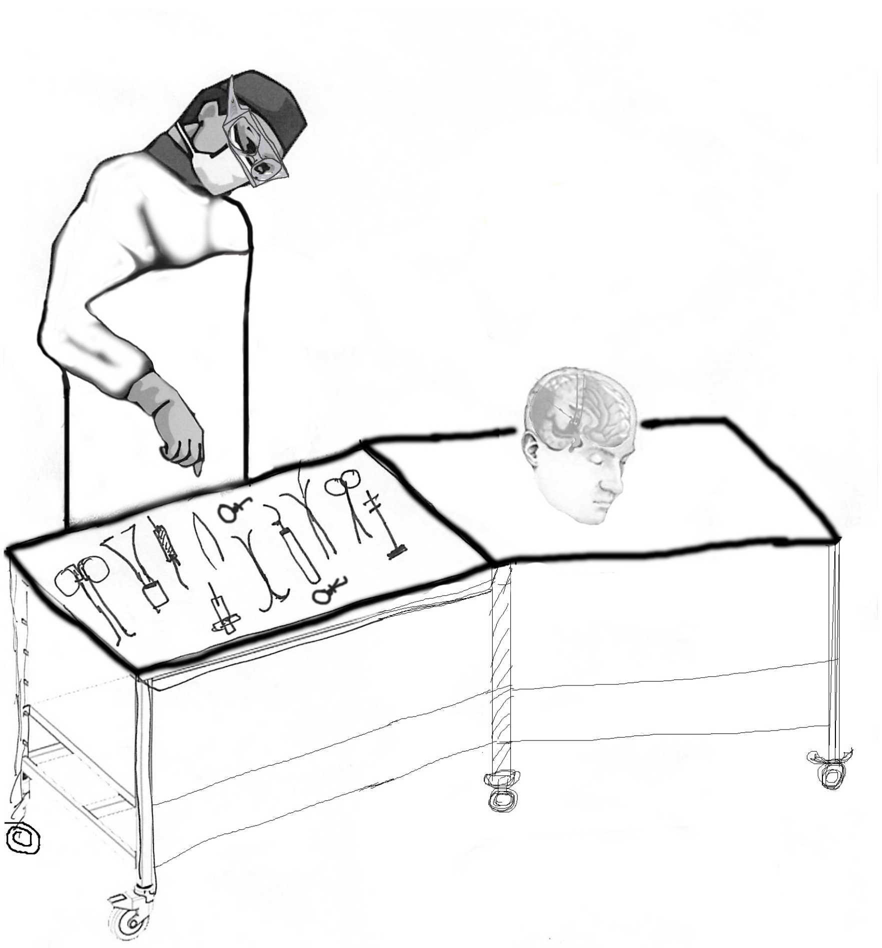

Figure 3.9: A simplified illustration showing a surgeon who is about to practice the treatment of brain aneurysm over a virtual patient's head

Mark picks up a medical tool, the system automatically shows a trajectory (as a set of animated dashes) hinting at the anticipated interaction possibilities and their impact, whenever possible (Figure 3.10). Moreover, the animation speed of the trajectory dashes will differ to notify the user of how quickly the interaction should be performed, utilizing the temporospatial element of "velocity".

The visualization enables (de)activation of floating graphical user-interface elements that reflect critical medical information (e.g., MRI data, current brain damage) and controls (e.g., to stabilize breathing or heart rate). Some of these visuals can be superimposed over the virtual head as needed.

During the procedure, a complication representing the aneurysm rupture occurs and Mark is

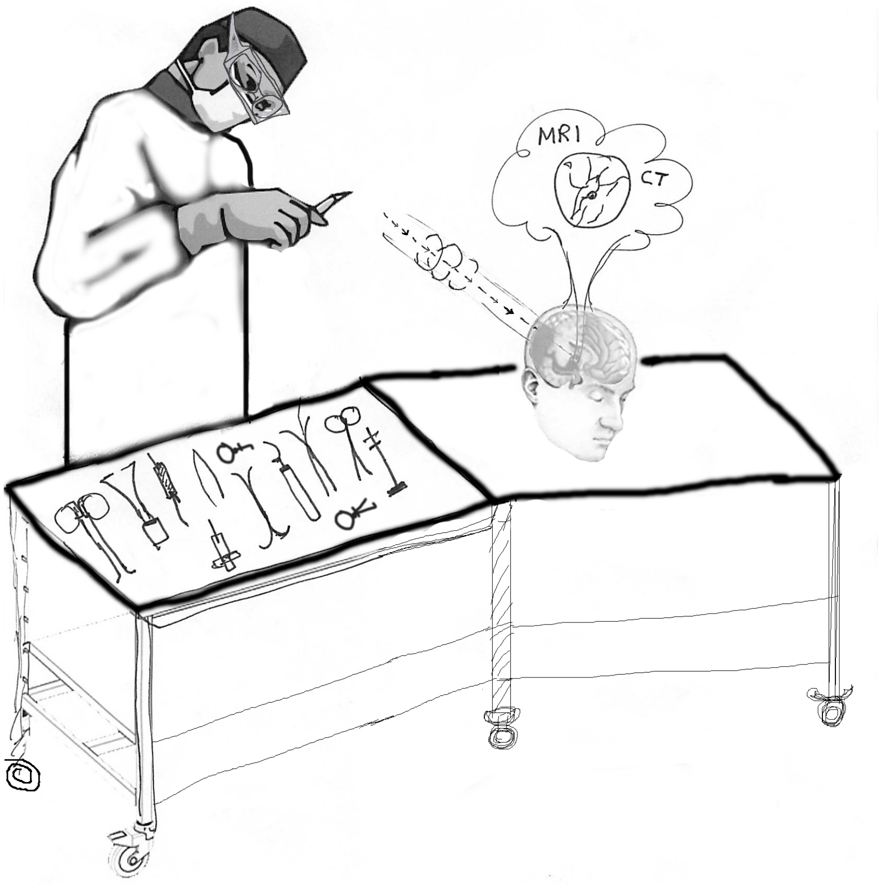

Figure 3.10: An illustration showing a surgeon who picks up a medical tool causing the system to hint at a possible interaction trajectory with other floating visualizations

expected to react to save the patient's life (Figure 3.11). In this critical and time-sensitive situation, there may be a need to handle other critical issues (e.g., the injection of certain fluids). Here, the system's interface can support Mark in different ways through the temporospatial interactions. For instance, a floating visualization appears in space with changes over time reflecting how much damage has occurred to the brain. Also, the color of the affected area will be animated, highlighting where the damage takes place. Moreover, the interaction trajectory could depict its dashes with faster animation reflecting the need to interact quickly. Finally, a temporospatial clock appears hinting at the amount of time (normalized as one cycle) available to save the patient's life.

Mark realizes that he cannot quickly handle the situation. So, for training purposes, Mark decides to slow everything down (i.e., activate temporospatial scaling mode) to give himself a

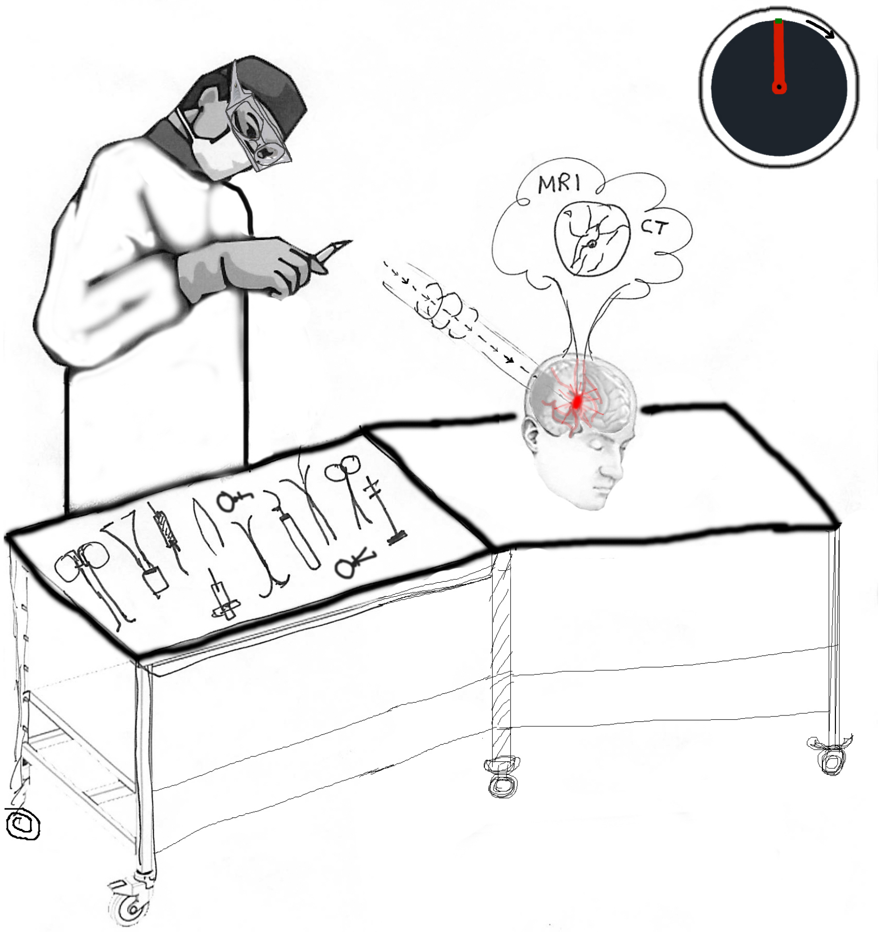

Figure 3.11: A sketch of the system highlighting the affected area whenever a complication arises with a special clock hinting at the available time remaining to save the patient

better chance to fix the situation and improve his decision making and reaction time. While such temporospatial manipulation is unrealistic, it reflects a starting point that allows the user to train and help him succeed, by gradually adapting his skills to reality. To activate this temporospatial mode, Mark moves the solid green square (the tip of clock handle) down, effectively scaling the clock's hand and forcing the simulation to run 50% slower than the real time which is depicted as a transparent hand (Figure 3.12). In addition, the visualization also provides Mark with various transitioning effects to notify him of entering in/out of this temporospatial scaling mode.

Figure 3.13 shows different examples of manipulating the hand of the temporospatial clock. For instance, by scaling the hand down to a dot (as depicted on the far right), the user is effectively forcing the time to stop. When the user enters the temporospatial mode, a transparent hand always

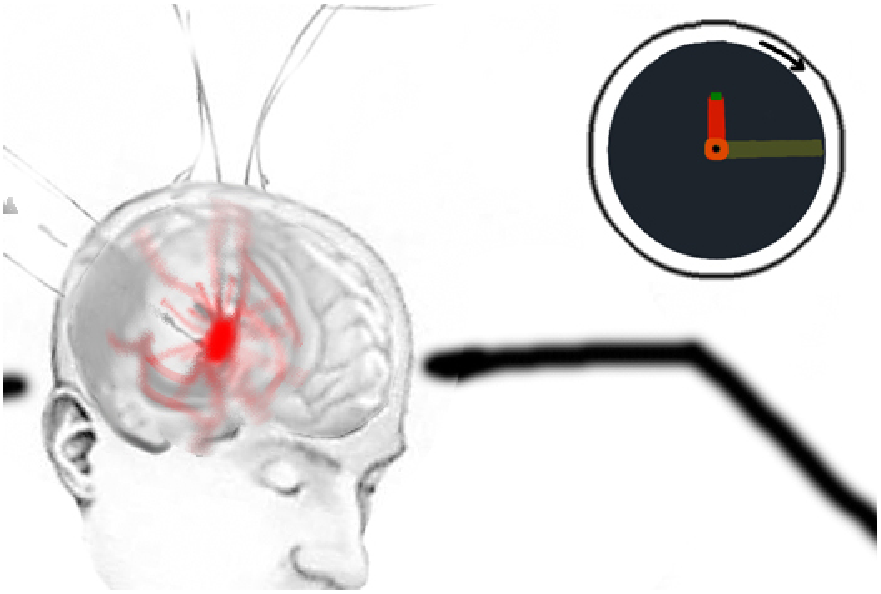

Figure 3.12: Illustrative visualization showing time/space scaling: the solid clock hand indicates that time is now running 50% slower than the transparent real-time indicator

reflects the real-time passing.

Interestingly, Mark can activate this mode of temporospatial scaling for different reasons. For instance, Mark may need to try an action and its impact before actually performing it. In other words, this mode utilizes the temporospatial element of "shadowing" to enable travelling in time and experiment with the anticipated action as if it were a reality. Without such temporospatial empowerment, Mark is only supported with typical VR interactions, which limits his capacity for reflection and learning.

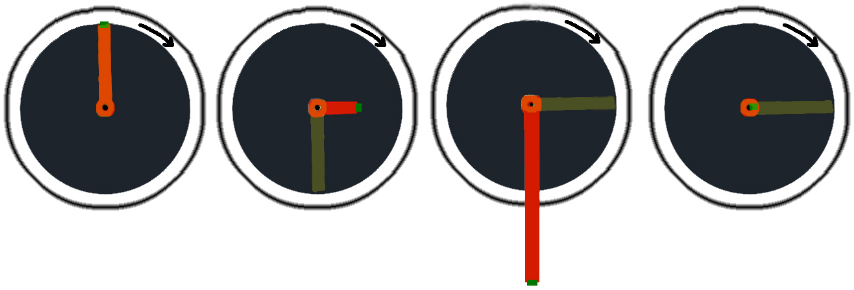

Figure 3.13: Different representations of scaling the hand to control the temporal rate, with the effect of (from left to right) no temporal scaling, making time slower, faster, or completely freezing it

3.4.6 Training and Repetitive Practice in Surgical Simulation

In this section, we briefly highlight our explorations of temporospatial learning aids in the context of surgical simulation. A more detailed explanation of the explored immersive environments and their potential for supporting experiential learning can be found in Chapters 4 and 5.

In our first experimentation, we explore temporospatial learning aids to provide on-demand guidance, contextual visualization, and to hint users at potentially harmful interactions (e.g., touching the spinal cord or nerves). We also incorporate simplified haptic feedback to help achieve different tactile sensation that are critical for surgical procedures. The novel utilization of visual scaling, as a temporospatial learning aid, causes currently selected surgical tool to be enlarged for enhanced interaction during the simulation. In Chapter 4, we detail the design, development, and evaluation of some of these ideas.

In Chapter 5, we focus on exploring a specific temporospatial learning aid for empowering users' memories and supporting (deliberate) repetitive practice within the surgical context of pedicle screw insertion. In particular, we focus on allowing trainees to reflect on and utilize their interaction history through a novel representation aimed for spatial immersive environments. Through this visualization, users will not need to restart the simulation every time they do actions with unintended consequences. Instead, users will be able to undo and redo their interactions as needed. This unique learning aid enables users to travel in time and explore different alternatives of doing the same action. Ultimately, users would be empowered to learn from their own mistakes and could share how they approached the surgical task with other fellow learners or the instructor.

3.4.7 Gamified Training Simulation for Landing Oil Rigs

Oil and gas simulations can also benefit from novel explorations of learning aids. In the context of landing oil rigs, a safe and semi-realistic immersive environment would be helpful in supporting experiential training for domain experts. Inspired by gamification, we have prototyped an immersive training environment for landing oil rigs (as detailed in Chapter 6). For example, we integrated various superimposed spatial indicators to provide visual warnings on unexpected task conditions (Figure 3.14). This is similar to how games inform players of action consequences or when hinting the players at what is happening.

Figure 3.14: Illustrative demonstration of how game ideas can be used as learning aids in immersive practical simulation.

3.4.8 Humanoids as Instructors

Our examples so far have focused on the environment itself and how it could be enriched by learning aids. In this example, we take a different approach, and introduce an additional factor to enable unique experiential learning experience, especially when human instructors are scarce.

We use the context of training for industrial assembly tasks, and we consider deploying humanoid robots as instructors in such context (Figure 3.15). Training for industrial assembly requires workers to become familiar with all steps of the assembly process, including learning and reproducing new tasks, before they can be employed in a production line. The derived challenges in current training practice are limited availability of skilled instructors, and the need for attention to specific workers' training needs. Humanoid robots can become the main learning aid in such

Figure 3.15: A humanoid teaching learner how to assemble an object.

scenario to teach assembly tasks to workers while also providing a quality learning experience (See Chapter 7 for detailed description of this project).

3.5 Conclusion

Current design practices of interactive learning environments often pay little attention to the rich, open-ended temporospatial possibilities and learning aids that these immersive environments enable. Our research proposes a framework that attempts to open a discussion and provides insight into the challenges and needs of educational aids in immersive environments to enable experiential and quality learning experiences.

We discussed that a rethinking of learning aids including temporospatial elements in the design of everyday immersive environments is beneficial. We demonstrated through some examples how temporospatial learning aids can be used in practice. We detail some of the mentioned examples and ideas in the following chapters of this dissertation, and we hope that this research will encourage further discussion and consideration of temporospatial learning aids in the design of everyday immersive systems.

Chapter 4

NeuroSimVR: Applying Educational Aids Within A Virtual Reality Spine Surgery Simulator

In this chapter, we contribute NeuroSimVR, a stereoscopic virtual reality spine surgery simulator that allows novice surgeons to learn and experiment with a spinal pedicle screw insertion (PSI) procedure using simplified interaction capabilities and 3D haptic user interfaces. By collaborating with medical experts and following an iterative approach, we provide characterization of the PSI task, and derive requirements for applying this procedure in a 3D immersive interactive simulation system. We describe how these requirements were realized in our NeuroSimVR prototype, and outline the educational benefits of our 3D interactive system for training the PSI procedure. In essence, we explore educational aids within a surgical simulation context and report on how the explored aids could mediate experiential learning in this interactive context. We conclude the chapter with the results of a preliminary evaluation of NeuroSimVR and reflect on our interface benefits and limitations. It is worth noting that parts of the work presented in this chapter has appeared in the following publications [200], [199], and [158].

4.1 Introduction

Three-dimensional (3D) immersive simulation systems are common in many real-life contexts, aiming to better support learning and training [42]. Surgical education is one particular example wherein such simulation systems are becoming increasingly important to the extent of making them a part of the core medical curriculum (e.g., [9]). However, medical students and resident physicians are faced by many challenges when using these educational tools due to technical and user experience limitations. In particular, existing surgical simulation systems have focused primarily on accurate implementation of the surgical procedure (e.g., providing haptic feedback or having high-resolution rendering), while optimizing user interaction and user experience have been often weakly considered [96], [104], and [97]. Consequently, it is not surprising to perceive limited adoption of such simulation systems by some medical experts. Therefore, there is a need to mitigate the aforementioned challenges to widen the adoption of 3D simulation technology, and support medical experts with training and learning environment that better satisfies their needs and expectations.

One common task in surgical education and training pertaining to spine surgery is pedicle screw insertion (PSI) [122], which is the focus of our work. In this task, the expert surgeon identifies abnormalities of the spine such as spondylolisthesis and performs spinal procedures including PSI aimed to reestablish normal alignment and stability. To ensure successful operation and mitigate the potential complications of the procedure, the surgeon requires expertise in anatomy and surgical technique. By examining many of the existing spine simulation systems (e.g., [70], [103], and [80]), we found that they incorporate limited procedural context and only focus on visualizing the spine model and the needed surgical tools. With regards to interaction, operating many of these simulations can be complicated and cumbersome, requiring the user at certain moments, to interact via a variety of devices (e.g., keyboard, hand controller, tablet, foot pedal) at the same time without any interface guidance. In essence, our collaboration with experts revealed that users, particularly novice, need considerable training effort before they can use and operate many of such simulation systems. Therefore, we focus on supporting novice medical users with a 3D immersive environment that enables them to easily learn and train spine surgery procedures, while capturing all necessary elements in a simple and realistic way.

Along the way of developing an effective novel spine simulation system, we attempt to characterize the design process focusing on the challenges that pertain to optimizing the educational experience of PSI task. Our participatory design approach involves collaboration with experts from the fields of medicine and education including revisiting the design of educational aids for supporting spine simulation. We stress the importance of simplifying the simulation interface and interactions following the collaborators' feedback, and that the educational features should be integrated during the early design stage to maximize the quality of the immersive simulation and the overall user experience.

We propose NeuroSimVR [158], a 3D stereoscopic virtual reality simulation with unique educational features and simplified interactions, enriching how surgeons can learn about and practice the procedure of pedicle screw insertion. The proposed design was derived from participatory process involving meetings and consultations with medical collaborators. It was also our first approach towards re-visiting common educational aids in a practical context. The developed prototype includes intuitive integration of 3D display and haptic interfaces as well as interaction capabilities for supporting the education of spine surgery. We also report on the results of a preliminary evaluation we conducted reflecting on the efficacy of our prototype and the value of educational features in assessing the technical skills of surgical experts. It is worth noting to highlight that my role in this project involved the actual design, implementation, and evaluation of the simulation prototype. It also included drafting the project report for publication. My collaborators have provided feedback on the proposed design and implementation, and facilitated the recruitment of the medical experts for the conducted study.

The contributions of this chapter are as follows:

- Insight derived from participatory collaboration with medical experts regarding the design of spine surgery simulators.
- NeuroSimVR, an immersive simulation prototype with educational features that facilitate learning about and practicing the PSI procedure.
- The results of a preliminary evaluation of the developed prototype including reflections on benefits and limitations that could support future design efforts of spine surgery simulations.

4.2 Research Approach

In this research, we followed a participatory approach [205], working in collaboration with medical experts including residents, surgeons and education specialists. Our user-centred design follows existing guidelines (e.g., for 3D interaction and performing evaluation with domain experts [11], [215], and [78]), and explores better ways of supporting the experts to practice and improve their skill acquisition [65]. We are re-visiting specific educational design elements related to surgical simulation in order to enrich medical users with a usable educational and training environment. We focused on the task of (open) pedicle screw insertion that pertains to back surgery as a simple procedure with room for various educational aspects.

We had bi-weekly meetings with our collaborators to gather their feedback about the implementation progress and their suggestions for improvement. In this regard, we followed user-centered design methodologies from the fields of human-computer interaction [206] and virtual reality (e.g., [78], and [215]) in order to guide our characterization of the PSI task.

4.2.1 Task & Context Description

A human spine is composed of various vertebra levels and the pedicle screw insertion task is common in one or more of these vertebrae. Surgeons need to have knowledge about the anatomy of this area to perform this procedure. For detailed background about the this task and the steps involved in it, we suggest referring to Appendix A.

To verify our characterization of the specific field of spine surgery simulation, we developed a spine simulation prototype and conducted a study to evaluate its efficacy with regards to educational features and its simplicity for supporting the training of novice surgoens. It is worth noting that we used the task of pedicle screw insertion as our context, but our exploration and the developed simulation can easily be extended to support other surgical tasks. Indeed, our design and exploration of the proposed educational elements (below) are generic and can be adapted to almost any simulation-based education scenario.

4.2.2 Design Rationale

Many of existing back-surgery simulation systems (e.g., [122] and [248]) use 3D monitors and haptic interfaces to increase the level of immersion. However, such systems are still lacking some key aspects that could enhance user experience including giving the user control over the visualization of the task context and guiding the user visually while performing the task. Furthermore, the utilization of these systems for educational and training purposes is weak as many of them only focus on supporting the core functionality of the task without providing enough contextual aspects. For instance, a spine surgery simulation typically only includes the spinal bone model and lacks the surrounding nerve roots, a lack which could affect the educational value and the overall experience.

Examining Existing Simulators

Our collaboration with the medical professionals involved studying some of the existing simulations as well as using them, as needed. In particular, we have experimented with two of the common surgical simulations that include support for the PSI task, namely ImmersiveTouch$^{\text{TM}}$(IT) [104] and NeuroTouch [169].

Based on our exploration of the aforementioned simulation systems and the discussions we had with our collaborators, we identified that the limitations of current simulation systems stem partially from the complexity of interaction and the lack of educational features for supporting simple and effective simulation. In the IT simulator, for instance, we found that it requires simultaneous interaction and coordination across at least four different devices (e.g., an iPad, mouse, customized pedals, haptic device, keyboard, etc.) in order to use it, an apparent complexity that affects its usability. Also, the IT simulator only provides basic numeric score for reflecting user's performance, a limitation that poorly hints at specific improvement aspects. Concerning interface, the IT lacks support of visual guidelines that are particularly important for alignment when inserting multiple surgical screws. Finally, users of IT are limited when it comes to exploring and/or manipulating the surgical context prior to starting the actual simulation.

Our medical collaborators highlighted the need to support novice users and to only show the important features on demand. They also stressed the importance of having a more detailed performance feedback after completing the simulation. In this regard, we followed an iterative prototyping approach for the design of our prototype and focused on having simplified interaction capabilities and improved usability. For example, novice users can run our simulation with no need of any specialized devices beyond the essential haptic stylus and one keyboard button to interact and completes the simulation.

Usability Exploration and Educational Aids

During the consultation sessions with our collaborators and prior to designing our simulation prototype, we have identified and decided to focus on supporting specific usability criteria [170]. In particular, we aimed for *Learnability* (how easy is it for users to learn and use the simulation assuming no prior knowledge), *Feedback* (how errors should be handled and how user performance to be reported), *Efficiency* (the simplicity and flexibility of the interaction capabilities), and *Satisfaction* (intuitive visualization). In addition to targetting these usability criteria, we aimed to re-explore the following educational aids: on-demand guidance and contextual visualization, trajectories that hint at potential interactions, animation of specific objects to signify user's attention, interface elements' reduction to avoid overloading cognition, and having post-learning representation allowing learners to reflect on their performance.

In our design, the aforementioned usability elements and educational aids enable quality learning experience and help achieve the following learning goals. First, users should be familiar not only with the PSI procedure but also with the spinal context including the structure of nerves and muscles around the spine. Second, learners should easily practice the PSI procedure, which requires a simplified simulation enviornment. Finally, learners need to visually assess their performance and how they were able to perform PSI in comparison to how expert surgeons would do the task.

Towards supporting *learnability*, the design of our spine simulation prototype has included various educational aids that were explored and integrated following our collaborators' insight. Firstly, our simulation supported three stages: pre, during, and post procedure training. At the pre-procedure stage, the simulation would inform learning of the task context by providing users with the ability to control the visualization of the relevant surgical anatomy around the spine including visualization of the neurovascular structures (i.e., nerves and blood vessels) as shown in Figure 4.1.

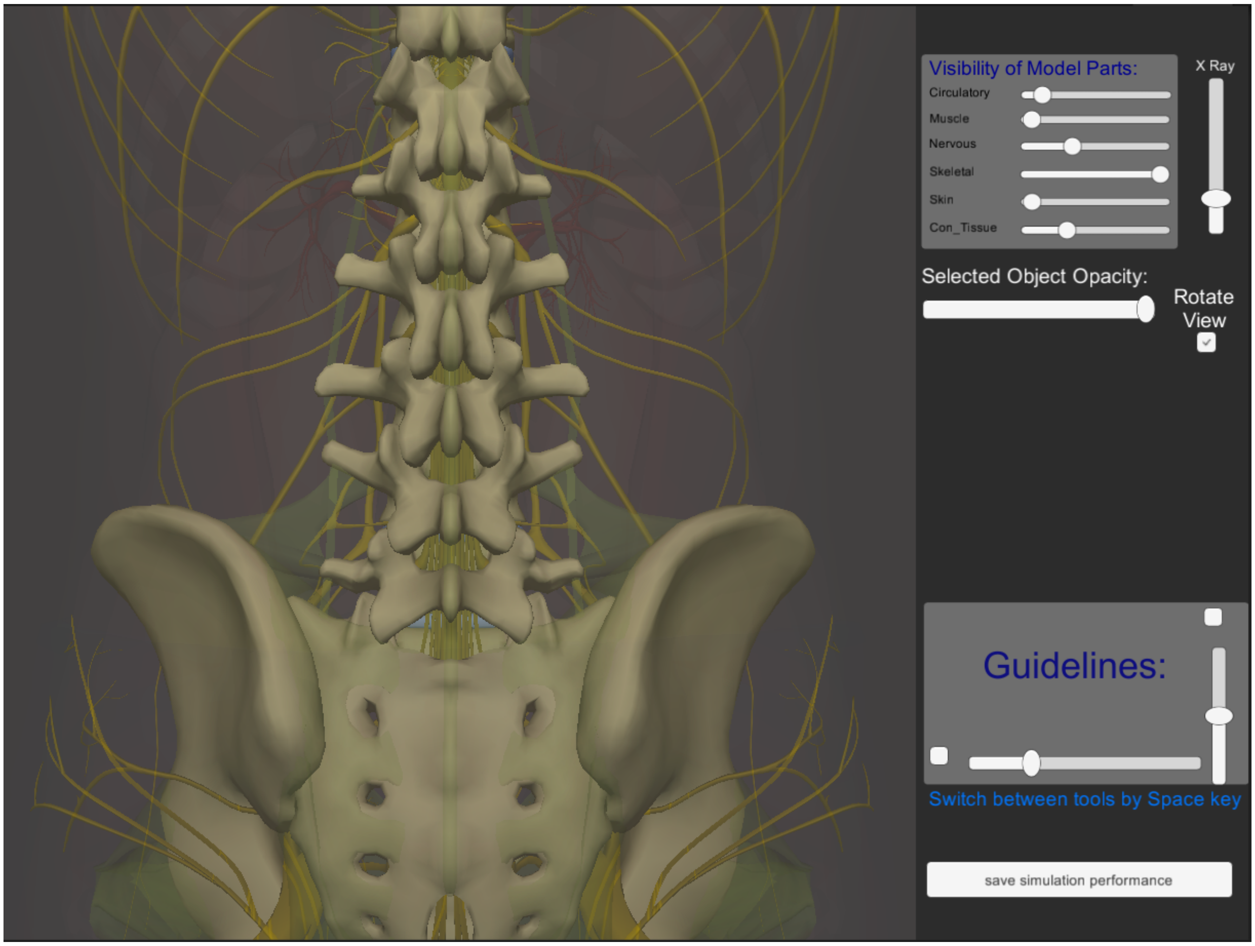

Figure 4.1: Visualization of anatomical context around spine (e.g., connective tissues shown in light green, nerves shown in yellow, muscles shown in light pink, etc.).

Secondly, the graphical user interface of our prototype has gone through various refinements. Most notably was hiding all unnecessary elements to simplify any potential occlusion or cluttering as suggested by our collaborators. One example here that reflects on having GUI on-demand is when the user is about to drill to make a hole at a particular location. In this regard, a 3D visual trajectory is shown to hint at the available depth and orientation of the drilled hole and to guide the user before the actual screw insertion (similarly to the approach proposed recently by Naddeo and others [164]). Such visual augmentation would simplify occlusion during the simulation and could support non-expert surgeons who have suboptimal screw placement. Other visualization decisions included showing guidelines that help users identify insertion points or landmarks consistently (Figure 4.2), as well as integrating interface-guidance aspects related to input and interaction (e.g., hinting that pressing the space-bar enables switching among the available medical tools). The proposed "guidance" allow novice users to utilize the simulation system without significant back-end technical support or a steep learning curve. It is worth mentioning that a good system tutorial cannot replace the proposed "guidance", which we argue goes beyond an interactive user manual to a smart dynamic in-situ hint that automatically complements user's awareness of possible interactions and alternatives.

Our design of the spine simulation also included an instructor-like mode. In this a mode, a skilled surgeon can describe what an ideal surgery performance would look like by defining where landmarks, holes, or screws should be created. This enables easier assessment of semi-skilled users and provides a learning opportunity wherein residents and novice surgeons can see how an expert would do it. The design of this mode also utilizes a XML configuration file that stores not only the prototype simulation parameters (e.g., simulation mode and GUI stats) but also the information of the ideal trajectory for each inserted screw.

In terms of supporting *feedback*, we decided to keep the user informed by relevant feedback particularly during the simulation. For instance, visual blinking occurs upon touching critical parts around the spinal bones (e.g., nerves). Also, graphical panels become visible (on demand) giving numerical feedback about current interaction while it occurs. For example, when drilling a pilot hole, a panel shows information about the hole being drilled including its depth and the entry angle and location. It is worth noting that the aforementioned feedback ideas also contribute to supporting *learnability*.

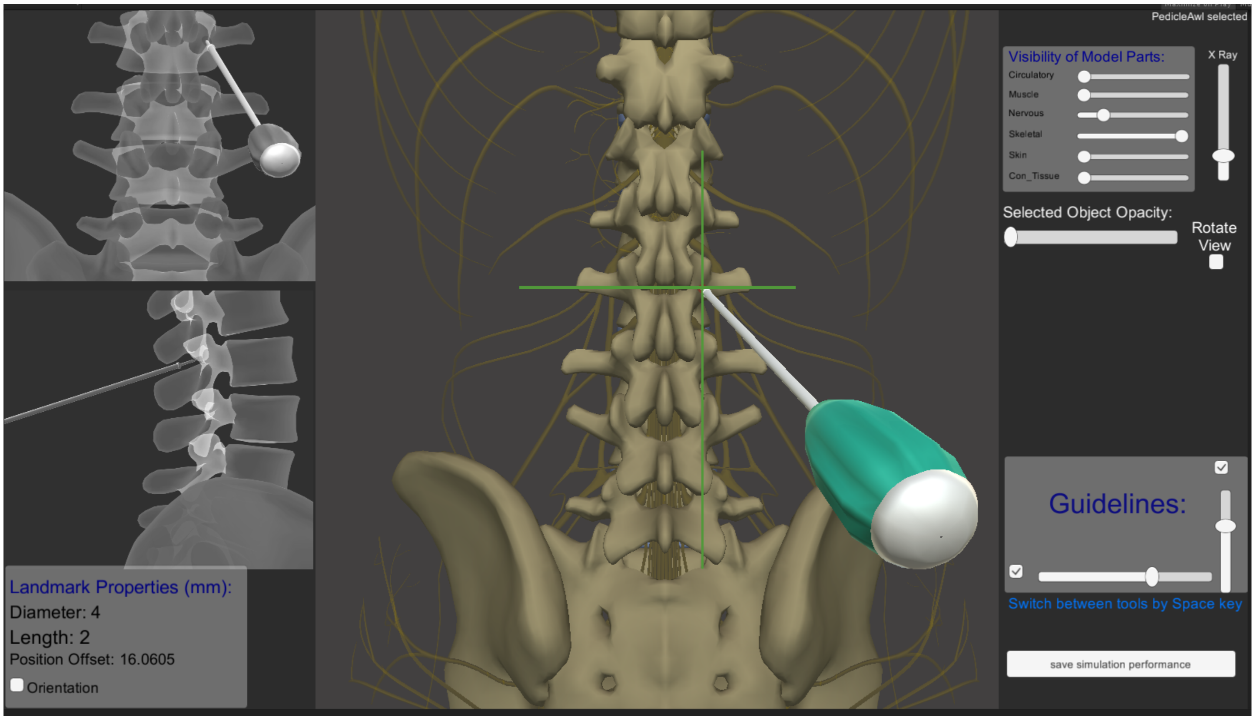

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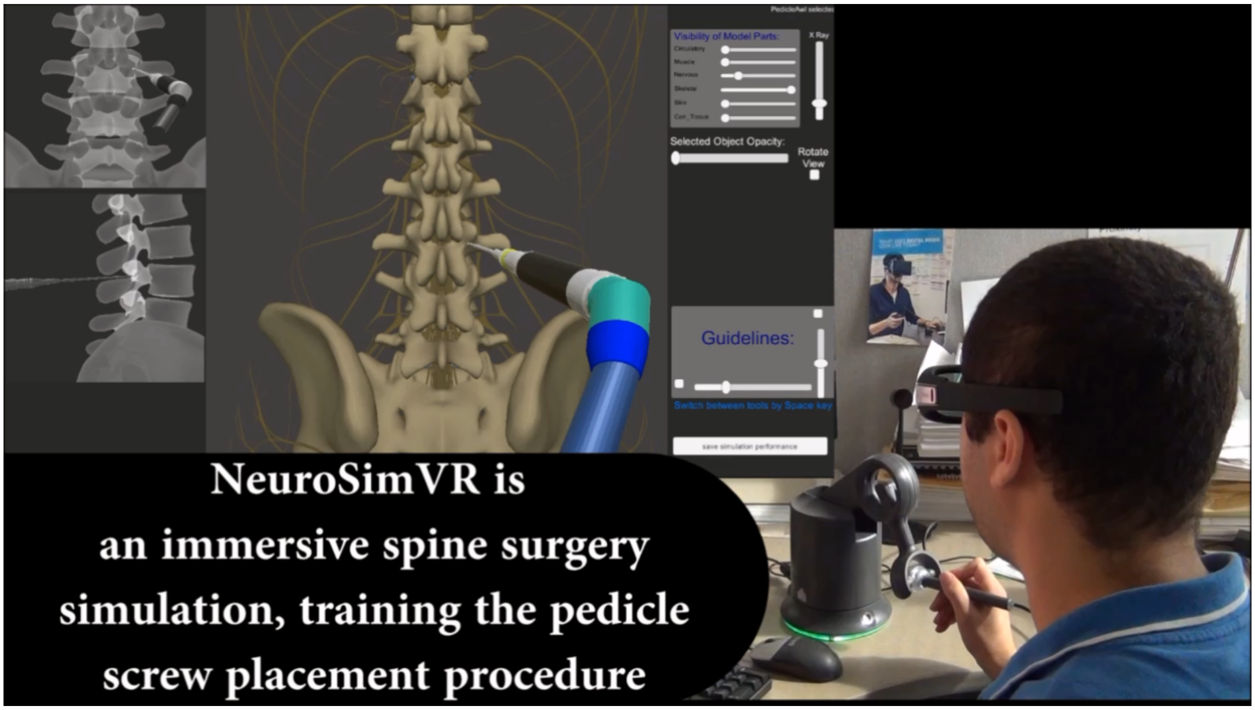
Figure 4.2: Guidelines are visualized (in green) to assist in screw placement.

By completing the simulation, the user can rotate and move the spine model to see his or her performance from other perspectives including isolating a particular vertebra for visual analysis. In this regard, the simulation is freezed and the ideal interaction paths, as recorded by expert surgeons, can be shown for reflection and examination. Also, the user can review many of the numerical performance metrics reported in this screen such as the time spent in simulation, screw depth, distance to ideal landmark entry location. These quantitative values may also be saved for later examination, and can be part of a full comprehensive future work evaluation. Such features represent a type of *feedback* that is particularly important for educational purposes, and for hinting at user mistakes that are difficult to notice from typical visualization.

4.3 NeuroSimVR

We developed NeuroSimVR (NS), a fish tank [240] (stereoscopic) virtual reality spine simulation prototype to support learning and training the surgical procedure of pedicle screw insertion. NeuroSimVR supports visualization of the spine and its context, haptic interaction capabilities, and X-ray views for guiding user interaction during the simulation similarly to what actual surgeons have in real operation rooms (Figure 4.3).



NeuroSimVR is an immersive spine surgery simulation, training the pedicle screw placement procedure

Figure 4.3: The interface of NeuroSimVR Simulator: X-ray views (left), perspective 3D view (center), and GUI controls (right).

4.3.1 Implementation

We aimed in our implementation of NeuroSimVR on utilizing a development environment that enables rapid prototyping and flexible integration of interfaces devices. Therefore, we used Unity3D v5.4 and the MiddleVR framework v1.6 [145] with Windows 10. During the implementation process, we experimented with a variety of stereocopic displays and haptic interfaces for increased efficiency. Our experimentations focused on supporting depth perception during the simulation, and therefore, our prototype utilized an Asus 3D-monitor with NVIDIA 3D Vision (v2) and active 3D stereoscopic glasses. The computer we used had a Nvidia GTX 980 graphics card, which was able to provide a 120 Hz refresh rate consistently while running the simulation in Unity. Our setup also involved configuring the 24 inch 3D monitor with its native resolution of 1920 by 1200 pixel.

Haptic feedback is one important element for *effective* surgical simulation. As one of our surgical collaborator experts mentioned, *"Haptic feedback is important when the pedicle finder [tool] break through the bone [as it] will significantly improve the simulator"*. In this regard, we first explored Novint Falcon to support haptic feedback, but decided to look for another alternative due to the limited capability of that device (only three degrees of freedom and being less natural concerning how it is held). We switched to using Touch 3D stylus from 3DS Systems that supports six degrees of freedom and feels more natural with its pen-like interface. In fact, the physicality of the Touch is particularly suitable for attaching physical surgical tools to its end, simulating how a real medical tool is used in actual surgery. A challenge associated with attempting to support haptic feedback is finding simple and effective haptic software libraries, as many of them are quite complex and require understanding of low-level concepts of physics before using them. For our implementation, we used the Geomagic Unity plug-in v1.7 that acts as a layer of the well-known OpenHaptics toolkit [81].

By the end of using our simulation prototype, post-simulation data is displayed allowing the user to view his or her performance/score. Furthermore, the user can select a pedicle and make it re-oriented for comparison with an ideal set of landmarks or screws, which have been previously recorded by an expert surgeon. Such empowerment enable visual assessment, reflection and review of user interactions.

Figure 4.4 illustrates an example of the simulation performance statistics (e.g., time and screw depth), and shows an analysis that can be performed over the pedicle containing the user screw.

4.3.2 Prototype Components

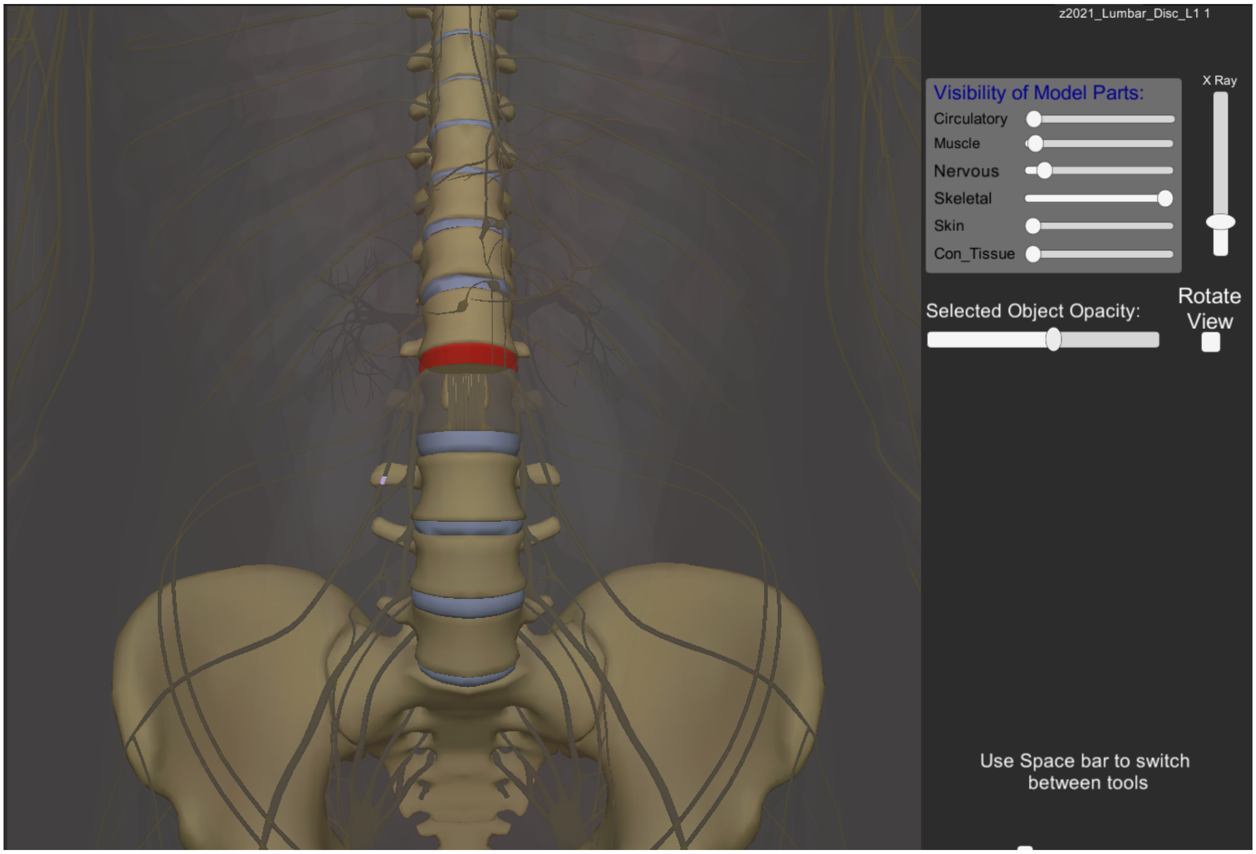
NeuroSimVR consists of three components. Each of these modules involves one or more Unity C# scripts that we designed for scalability reasons. The first component renders the 3D model of the spine and its surrounding anatomy (e.g., nerves and muscles). We used the 3D patient data from the Lindsay project at the University of Calgary [174]. The data was organized as a set of submodels

Simulation Stats:
Time(sec): 114.52
Distance to Ideal Entry (mm): 8.964998
Entry Angles (Lateral): 0.498657
Ideal Angles (Lateral): -6.999756
Nerve Contacts #: 12
Screw Depth (mm): 43.87574
Breach Grade: 0
Landmarks #: 1

Figure 4.4: Analyzing screws post-simulation: user screw (right) and ideal placement (left).

layered by the category of each anatomy (muscles, nerves, bones, etc). This component renders the complete patient data by assigning a specific material to each anatomy group allowing the user to interact directly with specific parts such as selecting a particular vertebra and adjusting its opacity, thus visually revealing hidden neural structures behind the vertebrae. Figure 4.5 shows an example where the user has adjusted some of the sliders to control the opacity of various anatomy parts. The figure also shows the user selecting one of the spinal disks. Also as a future direction, this component will support incorporation of patient-specific data on the fly, thus providing training over a particular patient's data before the actual surgery.

The second component manages the different GUI elements including specially render-to-target cameras (utilizing Shader programs) to provide a fluoroscopy (X-ray) view of the spine model (Figure 4.6). These cameras are configred and placed in particular locations to filter out and control the order of rendering specific 3D anatomical structure in order to achieve a realistic X-ray output (e.g., only the bones and the metallic tools are captured). Given that intraoperative fluoroscopy is one of the main sources of real-time feedback in spinal procedures, realistic representation of this component will allow direct transfer of surgical simulation practice into the clinical setting. In other words, our focus on this component and the first one highlights how we

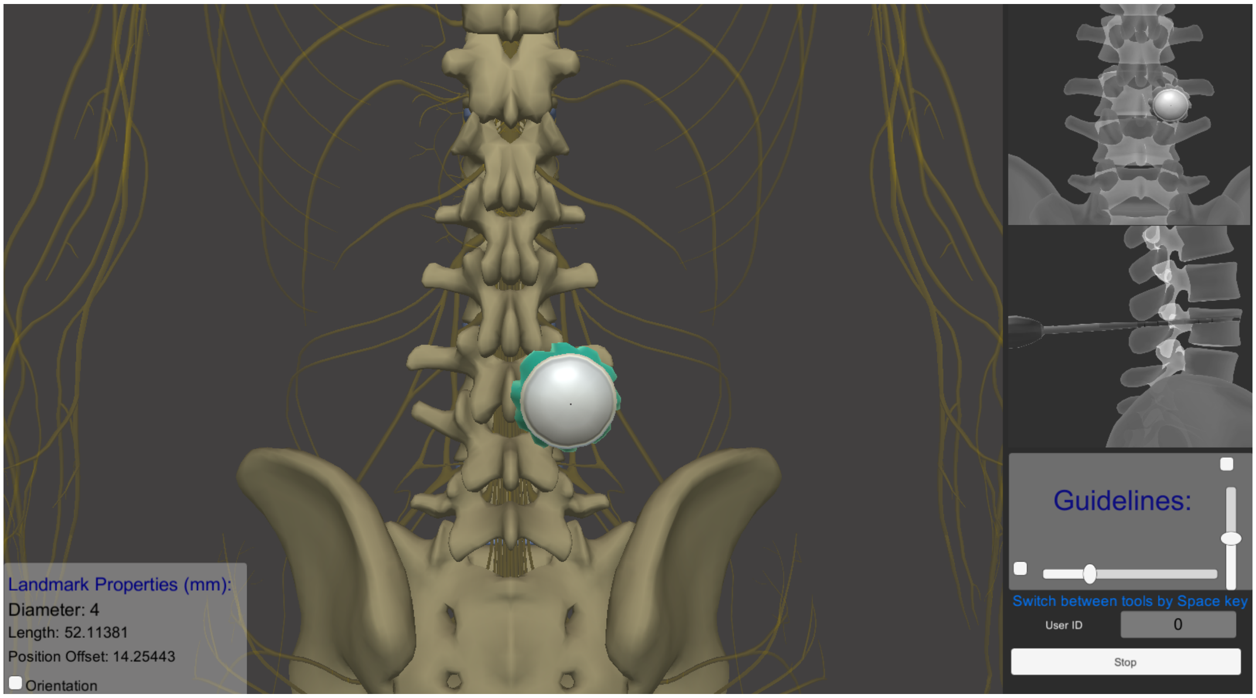


Use Space bar to switch between tools

Figure 4.5: A disk (shown in red) is selected with the lower vertebra transparent, highlighting behind neural structure.

aimed for user *satisfaction*.

The third component is responsible for supporting haptic feedback and controlling the different haptic properties. In particular, through our implementation we adjust a set of haptic parameters including stiffness, friction, puncture-level to enable the feeling, for instance, of interacting with bone versus soft tissue. In particular, we update such parameters based on the result of colliding the surgical-tool with the patient 3D data. For instance, once the surgical tool's tip touches the bone structure we update the haptic paramters to provide feedback that it is harder or impossible to penetrate the structure. Finally, a simplified state-machine component is responsible for handling the flow of the task, and notifies the user of his or her mistakes. For example, if the user touches the spinal cord while attempting to insert a screw, this component would cause the spinal cord to viusally blink, and would record this touch as one of the user mistakes during the simulation.



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Length: 52.11381
Position Offset: 14.25443
☐ Orientation

Figure 4.6: The pedicle-probe tool is selected to create the pilot hole, with a highlighting visualization in the X-Ray views.

4.3.3 Illustrative Walkthrough of Spine Surgery

We overview a simplified walkthrough of performing the PSI task using our prototype. The user starts by deciding on a particular area of the spine (e.g., lumbar, thoracic) for surgical training. Then, the user moves the X-ray sliders to that area, and adjusts the visualization of the spinal's context as needed (e.g., making nerves transparent). Now the user is ready to perform the actual steps of the surgery. The user then selects the “Pedicle awl” tool to create a surface landmark reflecting an entry point at a specific location as determined by the anatomy of the patient. The created landmark will have a graphical trajectory that highlights the possible insertion direction at that point (i.e., landmark trajectory). After that, the user switches to the “Pedicle probe” tool and drills a hole (at the previously created landmark) with depth and orientation that are suitable for the treatment. Then, the user switches to the “Screw” tool, customize its length and diameter, and initiate the screw insertion in the previously created hole by touching the landmark trajectory. Figure 4.7 highlights what the simulation may look like after performing the aforementioned steps.

The previous steps can be repeated for as many screws as needed to complete the treatment.

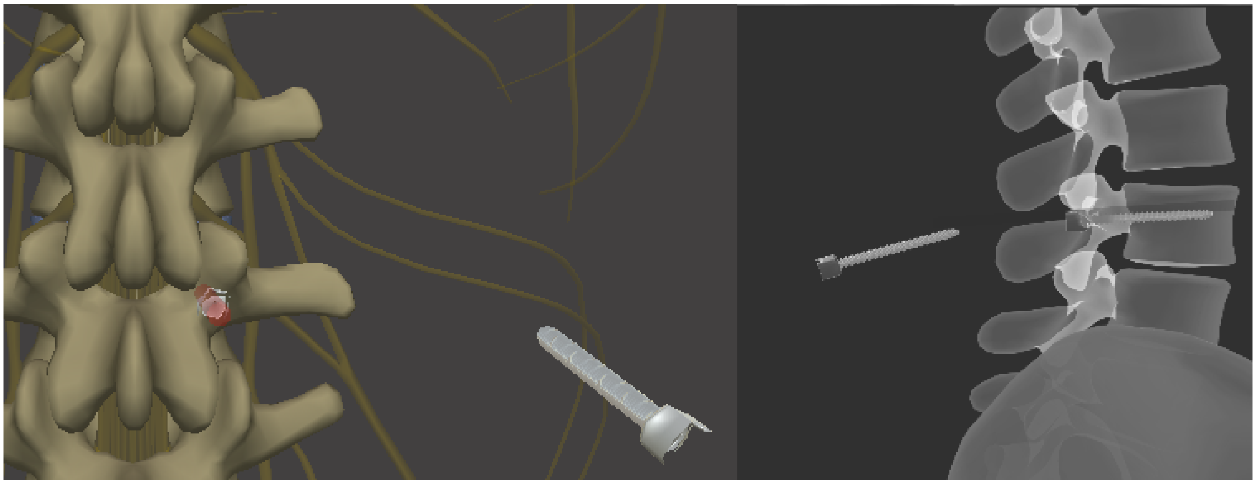


Figure 4.7: Visualization of NeuroSimVR after inserting a screw at the visualized transparent landmark trajectory shown in red.

4.4 Evaluation

We conducted a preliminary study to gather feedback from both design experts and surgeons about their experience towards our spine simulation system. We hypothesized that providing educational features and simplifying the interface of spine surgery simulation would benefit medical experts who want to learn about and practice spine surgery. A secondary goal of our evaluation aimed to assess the usability and potential of our prototype as an educational tool without focusing on measuring immersiveness aspects. Towards validating our hypothesis, we asked our participants to go through the simulation of a simplified surgical task. We gathered subjective feedback through the implemented survey and interview questions we provided. Our evaluation involved the use of our prototype as well as a known commercial spine simulator called ImmersiveTouch^{TM}(IT) [104]. The IT simulator can be described as a system that seamlessly integrates haptic feedback with a head and hand tracking and a high-resolution stereoscopic display to enable objective education and proficiency training of various surgical procedures including spine surgery 4.8. It is worth noting that we only considered the IT simulator (not NeuroTouch) for its popularity and because it

Figure 4.8: Overview of the ImmersiveTouch simulator used in our study.

better supports the PSI procedure.

4.4.1 Participants

We gathered feedback covering two different perspectives about our simulation prototype. Therefore, the participants of our study were distributed in two separate groups. The first group involved 6 independent participant surgeons (5 M / 1 F) of varying expertise including junior and senior residents as well as staff neurosurgeons. Two of our medical participants had some familiarity with the ImmersiveTouch simulator, but not with the specific PSI task we focused on. All of our participants tried the simulators and provided feedback. It is worth noting the recruited medical experts represents more than half of the residency program, which is comprised of no more than 10 experts. The other group consisted of 6 design experts (3M / 3F); computer science (CS) graduate students whose work involves visualization, design, and/or human-computer interaction.

While the consideration of CS/design participants may seem unnecessary as they are not the intended target audience of such simulation, we still included them because we wanted to gather some feedback about the design elements and the interface of the simulation. This feedback would be valuable for ensuring that the design of our prototype follows common design guidelines. The same can be said about including novice medical participants although we acknowledge that the validity of such prototype would be better established with expert surgoen participants [124].

4.4.2 Study Design & Procedure

We used a within-subjects design approach where we asked each participant to perform a simplified PSI task (as described earlier in section 4.3.3) using our simulator as well as using the commercial ImmersiveTouch simulator. The IT simulator utilizes specialized pedals for specific interactions as well as a high-quality haptic robotic arm. Our choice of the IT simulator, as our baseline, was because of its common use in many surgical education-based simulation scenarios [180] including the procedure of PSI [80].

The two simulators used in the study were set up next to each other with the participants performing the procedure in randomized sequence to avoid learning bias (Figure 4.9).

Prior to doing the study task, participants received training of the simulation and its usage. Then, each participant tried the PSI task and completed a survey using a 5-point Likert-scale for all questions. Finally, a post-study interview was administered, with the duration of each study session being around one hour.

The two different groups we had followed the same study protocol (i.e., going through the same simulation training and performing the same task), but since the goal of inviting CS participants was to focus on evaluating the design elements and the interface of the simulation rather than its context of use, we additionally asked the CS group to complete a system usability questionnaire [25]. The survey used in the study also differed slightly since some of the questions deemed less applicable to the CS group (e.g., asking if each simulation supports skills applicable to the operating room).

Figure 4.9: Study simulators setup: our prototype (left), and the ImmersiveTouch (right).

4.5 Results & Discussion

Most participants liked the various educational design elements we integrated in our simulation and hinted at their usefulness. On one hand, surgical trainees can use our prototype to practice and improve their surgical skill with regards to the PSI task, one of the most common spinal procedures performed by neurosurgeons and orthopedic surgeons. On the other hand, experts of medical education can use the prototype to illustrate certain concepts that relate to spinal surgery such as the importance of avoiding major complications such as injury to the spinal cord. Such insight is supported by the subjective feedback we received as well as how our participants have rated the different features of the developed simulation. As one of the medical participants said, *"If I am a professor, I will get that tool [referring to our prototype] because it is very easy to handle* *than this one [IT]"*. Such a comment reflects positively on our simulation's potential to address the *learnability* factor. In essence, the results of our evaluation, in part, may reflect that our simulator has successfully achieved face and content validity [142]. It is worth noting that our focus on assessing user experience aspects may not fit existing surgical-simulation validity measures, and therefore, we argue for a new type of assessment that we call experience validity.

Our first prototype did not include support for important anatomy features such as nerves and blood vessels, but later we decided to add these features as valuable context to the current prototype based on the feedback we gained from our collaborators. The expert expressed that *"having anatomical features that can be manipulated (by making some parts transparent) may be very beneficial to anatomical education"*, and therefore, we supported the capability to control the visualization of these spine contextual features.

We divided the analysis of the study results differently for each group, and in the next part we first detail the CS-specific results followed by results of the medical group, and finally we describe the shared results from both groups.

4.5.1 Design Experts' Results

We report how the CS group rated our features as shown in Figure 4.10. Along the same line, we asked all CS participants to complete a System Usability Scale questionnaire [25] for our simulation as well as the ImmersiveTouch simulator. The average SUS usability score for our simulator was 80.41 out of 100, and 37.5 out of 100 for the ImmersiveTouch simulator. This result supports the *satisfaction* of CS group participants with regards to our simulator. This seemingly large difference in scores may reflect that our system was judged to be more usable by our design participants who went through the simulation and performed the simplified task, which contributes to the *learnability* aspect of our system. Furthermore, the qualitative feedback reported in the Discussion section below supports this interpretation. Finally, it is worth noting that all CS participants reported that they felt mentally and physically more comfortable in our simulator.

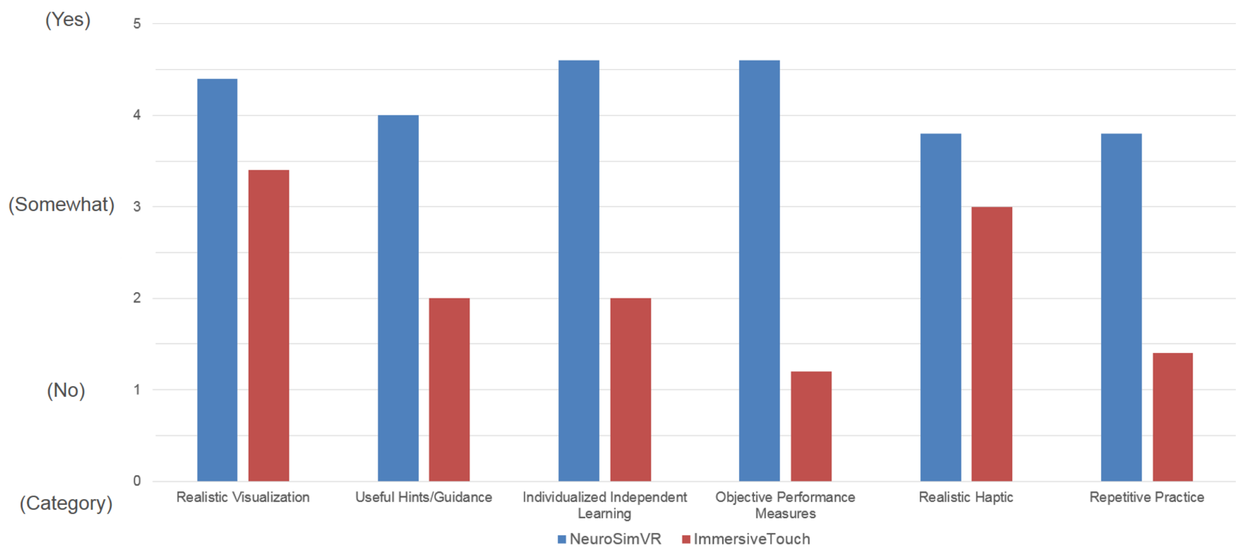


Figure 4.10: Rating of simulation features by the CS participants for both simulators

4.5.2 Medical Experts' Results

The medical participants rated both simulators with regards to how they support skill transfer to the OR. The rating for IT was 4.1 out of 5 while it was 4.6 for our simulator. In addition, the medical participants provided feature rating simular to the CS group. This result is in Figure 4.11, showing that both simulators were almost identical with slightly better rating for our simulator for most features except the haptic feedback. This may highlight that our prototype was at least effective as the IT simulator.

Interestingly, the results of the CS group reflected better rating for our simulator while the medical participants' rating for both systems was almost identical. This result could be related to the difference in background and perspective that the non-medical participants possess about the design of the interface and the supported interactions. Also, another interpretation of this result may be because we designed our prototype aiming to enhance educational support over the existing simulator that we have examined. In general, our preliminary results reflect positively on the usability criteria we considered earlier.

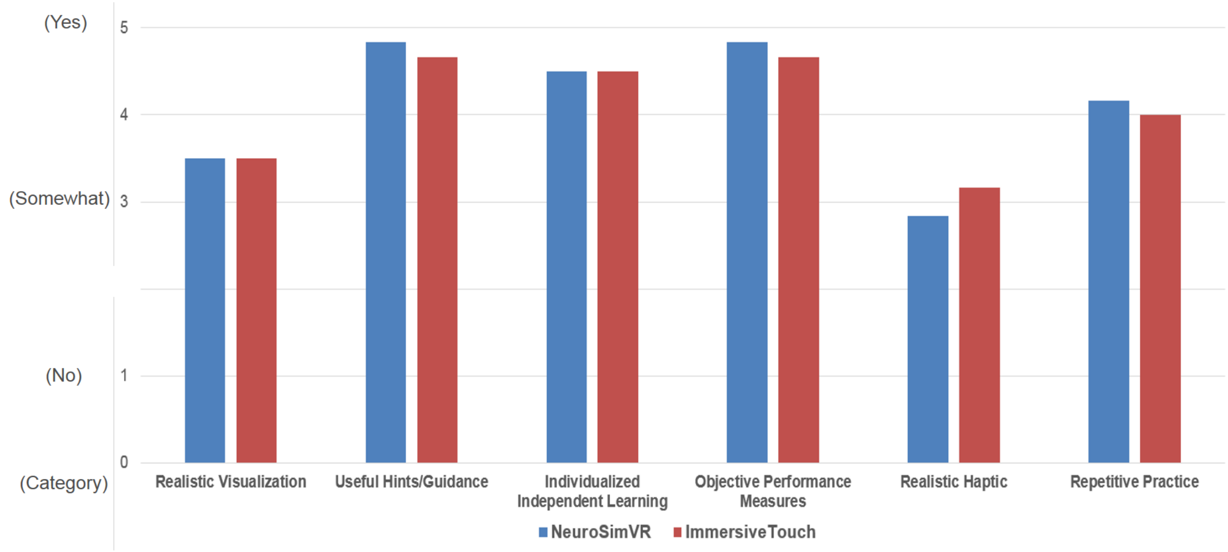


Figure 4.11: Rating of medical features by our surgeons' participants

4.5.3 Simulators' Strengths & Limitations

As a resident commented, *"The limitations of these two simulators are the limitation of any simulation; it is never going to be exactly [like] what it is in the OR in terms of the actual bones, nerve roots and the whole setting. In terms of strength, they are great for learning experiences"*. In this part, we reflect on some of the key strengths and limitations in each of the simulators we used, particularly with regards to supporting education.

Many participants mentioned the dispersed controls and the various devices for controlling the IT simulator as one of its key limitations, hinting at the difficulty of interacting with and operating the IT simulator. As P1 (a medical expert) stated, *"I think that with this one [IT], it was harder to figure out where the buttons and stuff needed to be. By having something in the first one [NS] that tells me where the pedicle is, my landmarks, and so on, it was perfect"*. A similar comment by a CS participant hints at the limited usability of the IT simulator, when he or she said, *"when I am using it [IT], I felt like operating an aero plane ... It did feel that I need spending more time and effort trying to concentrate on what I am doing; where are the pedals, ah it is somewhere on the left side, I have to look, push back, and then push back again; oh I have just lost the [hand] position of the haptic device, so I think I needed a lot of effort for using it, which was not the case* *for the other one"*.

Another limitation of the IT simulator relates to performance feedback, which is displayed after completing the simulation as a basic numeric score. As one medical expert stated, *"The measurement [of the performance feedback of NS] are better than just the score [provided by IT] as it tells us what angle was wrong and it shows us where we entered [the bone] as compared to the ideal trajectory, which is very useful for getting oriented. In fact, this helped me orienting myself with respect to the model"*. Interestingly, another medical expert participant suggested to adapt performance feedback according to learner's skills by providing real time feedback (at all times) for juniors and only showing it at the end for senior users.

Most participants, however, highlighted that the haptic feedback was more realistic in ImmersiveTouch. As one medical expert participant expressed, *"The haptic feedback [in IT] was not perfect but comparably better than this one [NS]"*. Also, one of the CS design participants felt that the rendering seemed a bit more realistic in IT due to the use of shading.

Our prototype also had clear feedback regarding its limitations. A key one as noted by numerous participants was that the NeuroSimVR lacked realistic haptic feedback. In this regard, we argue that this finding is in part because of the expensive high-quality haptic device [82] that is integrated with the IT simulator (e.g., the cost of our haptic device is roughly 30 times less than the IT one), and because the focus of our work is not about improving the haptic feedback. Nonetheless, we aim as part of our future work to improve our implementation of the rendering and the haptic feedback.

On the positive side, most participants liked our simulation and the various integrated educational elements. These include the flexible and simplified interaction, the real-time x-ray visualization, and the post simulation performance measures. The following qualitative comments are examples of the positive feedback we received. One CS participant commented about the availability of hints and guidance in design by saying, *"these are definitely useful. If I am someone who does not have any clue, hint or feedback would be useful to learn what is going on. If noth-*

ing happens, like in the existing systems [IT] there was no feedback for anything so I could have literally drilled holes across the person's spine and nerves and everything, and I would have no idea so I would keep thinking that I am okay; it is kind of pointless". Along the same line, one medical expert participant mentioned, *"I did like its 3D [referring to NS] as you can appreciate at the anatomy better than looking at the text book and that you can look the relationship between structures, and I like the fact that you can isolate one of the structures [levels] and see what is wrong [in your performance] and things like that".* Another medical expert comment also reflects on how the flexible interaction within NS supports learning about the anatomy and the context of PSI, when he or she expressed: *"The interactive thing [of NS] is quite helpful, with being able to see, I guess, bones and take away the bones and see where the nerves are and with the muscles on top, it just gives you a better idea of the anatomy".* Such results reflect on the usability aspects of our design rationale.

Our study had a limitation of small samples' size; 6 CS and 6 medical experts where we only performed basic statistical analysis on our data. Therefore, we refrain from making any significance claims. We highlight that our focus in this project was on interaction design aspects and less on surgical performance metrics (e.g., num of mistakes or the time each surgeon takes to complete the task). Indeed, our approach give more value to the subjective results received from the domain experts following the argument proposed by Greenberg and Buxton [86]. As a future work, this study can be expanded to include more participants and with additional focus on quantitative measurements.

4.5.4 Implications for Future Spine Simulation Design Efforts

Beyond having a more realistic haptic feedback, we argue that the following educational aids can be helpful for supporting future efforts of designing immersive spine simulations. First, we strongly suggest simplifying the design of interactions when building surgical simulation, as an important step towards providing more individualized independent learning. Second, the ability to adjust the visualization of each anatomy part should be supported. This includes giving the user the option to hide or show various contextual components as well as controlling their opacity. Third, as all participants stressed, it is important to provide performance measures that are meaningful beyond the simple numerical score provided by the IT simulator, similarly to the detailed reporting provided by our simulator. Fourth, integrating feedback in a timely manner can be useful especially whenever something goes wrong. For example, our simulator followed this approach and provided a basic notification (blinking) that informs the user when he or she touches a critical anatomy part during the simulation. Finally, it is worth noting how various participants highlighted that the rendering does not need to be realistic, especially for educational purposes, and reported that playing with visual perceptual cues would be more helpful (e.g., rendering nerves as contours and blurring out-of-focus parts).

We encourage designers of surgical learning systems to follow a design-based research methodology that enables iterative assessment of new educational interventions in a such real-life setting, focusing on examining how, when and why certain innovations may lead to enhanced learning experience. In the context of surgical education, for instance, it allows characterization of the algorithm required to bridge innovations in simulation technology and their implementation as training tools for residents [200].

To summarize, we argue that by including simple educational aids and closely following the feedback of medical collaborators, as we demonstrated in this work, the usability and the training quality of immersive medical simulations could be considerably improved. Furthermore, we suggest that educational features should be incorporated from the inception of the model rather than as an afterthought to maximize the chance of enhancing quality of the immersive simulation, the 3D interfaces provided to the medical practitioner, and the overall user experience.

4.6 Conclusion & future Work

We proposed NeuroSimVR, a 3D stereoscopic virtual reality spine simulation designed to support surgeons with a convenient environment to learn about and train the procedure of pedicle screw insertion (PSI). Our prototype was developed in close collaboration with medical experts and involved various design iterations to meet the expectations and needs of our users. We presented a preliminary evaluation highlighting the potential benefits of our 3D simulation in supporting education and training for the PSI spine surgery procedure.

NeuroSimVR is a work in progress prototype, and we are still improving it. First, we are considering the feedback we received to refine our implementation, for instance, by integrating external educational resources that pertain to back surgery and embedding them within the simulation interface for a better training experience. Also, we aim to support loading and displaying patient-specific data on the fly as deemed valuable. Another potential improvement would be to explore and support alternative ways to show and preview user history including 2D animated blinking snapshots. Finally, we aim to integrate interactive features to enrich advanced users with the ability to collapse/expand history paths, as needed. We are currently conducting a formal study focusing on PSI for different spinal parts (e.g., cervical, thoracic) to assess the practicality of our prototype for simulating different spine surgical procedures. This study is planned with actual medical surgeons and it would involve comparison with existing simulation systems.

Chapter 5

ReflectiveSpineVR: A Novel Approach to Supporting Repetitive Practice in Immersive Surgical Simulation

In this chapter, we contribute ReflectiveSpineVR, an immersive spine surgery simulation enriched with interaction history capabilities aimed to empower learners' memories and enable deliberate repetitive training. The provided interaction history features are based on a design study we conducted exploring what makes an effective interaction history representation in spatial tasks. Existing surgical simulation systems only provide a crude way to supporting repetitive practice where the simulation needs to be restarted every time. By working closely with medical collaborators and following an iterative process, we present our novel approach to enriching users with nonlinear interaction history capabilities and supporting repetitive practice including how such features were realized in our ReflectiveSpineVR prototype. We conclude the chapter with the results of a preliminary evaluation of ReflectiveSpineVR, highlighting the positive feedback regarding our history representation approach and the interface benefits. It is worth noting that parts of the work presented in this chapter has appeared in the following publications [159] and [160].

5.1 Introduction

Virtual reality and immersive simulation systems have been common for supporting learning and training within the medical domain. For the purpose of surgical education, many of the existing immersive simulation systems generally attempt to replicate the actual surgical context and focus on providing accurate implementation of the procedure (e.g., better haptic feedback or improved visualization) [142]. These systems particularly lack the flexibility to supporting repetitive practice, which is essential for developing surgical skills [96] and [97]. In other words, the lack of flexible ways to repeat the interaction or part of it during the simulation could impact surgeons' learning and training. Therefore, there is a need to explore innovative repetitive practice capabilities, as learning aids, that would better support medical experts while they train and learn about the complex flow of surgical procedures. Ultimately, such repetitive practice capabilities can be further enriched by the integration of intelligent tutoring approaches [184] that guide trainees and inform them of any incorrect behavior.

Towards empowering users' memories and supporting repetitive practice within immersive simulation contexts, we first present a design study we conducted exploring what makes an effective nonlinear interaction history representation in spatial tasks, which we termed ReflectiveHUD (RH). We argue that our novel representation reflects a unique learning aid that has the potential to mediate experiential learning in immersive simulation contexts. We propose ReflectiveSpineVR, an immersive spine surgery simulation with interaction history capabilities utilizing novel implementation of the RH representation and following the insight of our design study. Our goal is to assess how expert surgeons react and utilize the ability to control their interaction history and how such flexibility would support repetitive practice. Our prototype utilizes head-mounted display and 3D haptic interfaces and focus on the spatial scenario of back surgery and specifically the task of Pedicle Screw Insertion (PSI). Finally, we report on the preliminary results we gathered from medical experts reflecting on the potential of our prototype for supporting repetitive practice and the value of having effective interaction history features. It is worth noting to highlight that my role in this project involved the actual design, implementation, and evaluation of the simulation prototype. It also included drafting the project report for publication. My collaborators have provided feedback on the proposed design and implementation, and facilitated the recruitment of the medical experts for the conducted study.

The contributions of this chapter are as follows:

- The outcome of a design study exploring the potential benefits of using nonlinear interaction history models with insight into the different design variants towards having an effective history representation.

- ReflectiveSpineVR, an immersive 3D spine simulation prototype developed with nonlinear interaction history capabilities allowing surgeons to perform repetitive practice and improve their skills during the procedure of Pedicle Screw Insertion.
- The results of a preliminary evaluation of the developed prototype, highlighting how the participants liked our interaction history approach including reflections on how it could support future design efforts of surgery simulations.

5.2 Representing Spatial Interaction History

In this part, we begin by detailing the design study we conducted to explore how people perceive (nonlinear) interaction history representations in spatial tasks. Next, we describe how the insight we gained informed the design of our simulation prototype.

5.2.1 Design Study

We conducted a two-part study as a design critique focused on exploring what makes an effective nonlinear interaction history representation in spatial tasks. We explored two conditions in our study, an abstract tree visualization as our baseline condition, and the condition we termed ReflectiveHUD (RH) involving a set of enriched tree-like interaction history visualizations. We conceptualized RH using inspirations from games that explored innovative interaction history representations (e.g., [64] and [228]).

In the first part of the study, we aimed at gathering people's initial reaction to nonlinear interaction history representations. Then, we conducted the second part, utilizing some of the first part's findings, to gather a more focused feedback on the RH condition and explore design variations of the RH representation. In essence, this study aims to inform the design of the RH as a novel nonlinear history representation that captures and presents user's interaction over time. The insight of this study further informs how such history representation may be integrated in immersive simulation.

5.2.2 Structure

We recruited six student participants (1M / 5F) for the first study part and another different six participants (4M / 2F) for the second part, all from a local university with background in design, HCI, and visualization. We focused on recruiting participants with specific background to help us improve our ideas with their relevant design and visualization expertise.

Following a within subject design, we asked all participants to perform scripted spatial tasks. Prior to performing the tasks, the concept of interaction history was introduced through an example of undo/redo within the Microsoft Word application. Following each task, a short interview was conducted to elicit participants' feedback about history representations and their usage in this task. After completing all tasks, a semi-structured interview was conducted to collect how participants perceived the nonlinear interaction history visualization, their feedback on the various design encodings that were explored in the RH representation, and their overall experience. Each Participant was compensated $20 (CAN) for the study session that lasted one hour.

The participants were guided by (either hand- or computer- drawn) paper sketches reflecting specific instructions for each of the study tasks. Additional sketches were used simulating what the interaction history would look like at each step of the tasks.

Tasks

We chose simple scenarios reflecting interaction within a variety of spatial contexts: (1) finding a Santa Claus object hidden in the lab space, (2) making a flapping rabbit Origami object, and (3) building a (predesigned) Lego^{TM} construct. We scripted the tasks to simplify generating content for the history representation. We also chose tasks that reflect interaction within a variety of spatial contexts.

The first task focused on spatial exploration of the lab space. Each participant was asked to physically walk and search the lab following the experimenter instructions to fulfill the task with the goal of finding the Santa object in the lab. At certain (predefined) locations, participants were instructed to change their direction and continue the searching either to the left or to the right. At each step, an interaction history representation was shown reflecting their search progress so far and the direction changes they made.

In the second task, the goal was to make a flapping rabbit Origami object (Figure 5.1 right). The scripted instructions deliberately involved wrong steps (e.g., incorrect cut, unsuitable choice of colors, etc.) and ways to resolve them, allowing participants to rewind time and have another chance to fix the problem.

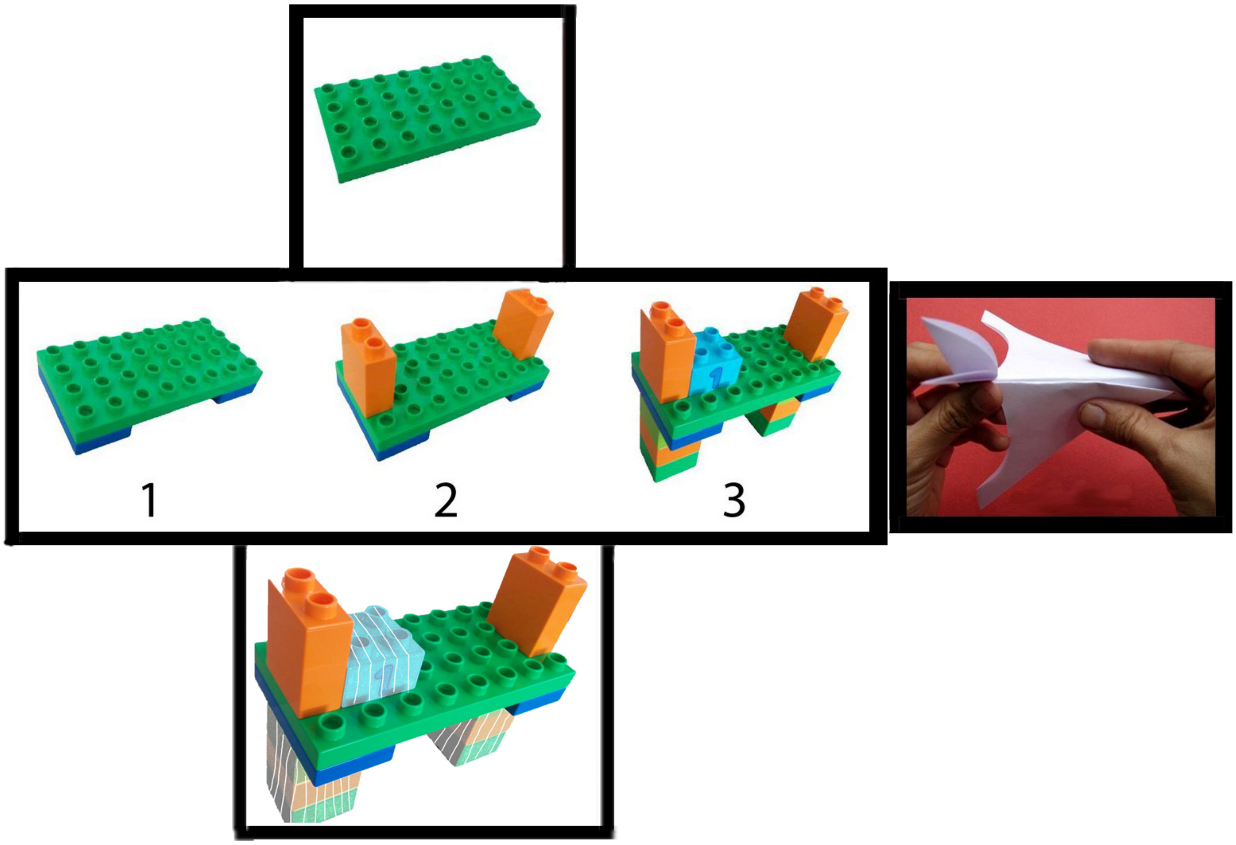


Figure 5.1: Sketches of the first three steps of the Lego task (left), and the desired outcome for the Origami task (right)

For the last task, we asked each participant to build a Lego shape. The instructions simulated how a user may refine the construction by changing his or her mind at certain interaction points.

For instance, the user was guided to arrange the Lego blocks, one after the other, in a certain way. However, later in the construction process and once the participant realizes that the current progress will not lead to the desired final shape, he or she was guided to roll back and try a different arrangement.

Examples of the sketches used in the first part of the study are shown in Figure 5.1 highlighting the first three steps of the Lego task. The figure also shows the associated RH history representation when the user performs an undo (reflected by hatched transparency for the Lego parts that were removed after the undo).

The sketches used in the second part of the study aimed to assess different design aspects of the ReflectiveHUD representation including transparency and layout. For the Lego task, the sketches focused on tree-like structures with random layout, aiming to visually highlight the branching points of the trees (Figure 5.2 left). For example, when a user performs and undo, to return in time to a previously saved node, and attempts to re-do the action, a new branch is created highlighted in the sketches by cloning the node and/or manipulating its transparency (e.g., disregarded tree branches reflecting history were made transparent). For the Origami task, two sketches focused on organized tree layouts (Figure 5.2 right), with one of the sketches reflecting a tree layout that only grows in a specific direction from the fixed root node from left to right and from top to bottom with a fixed location of the tree root. The second sketch assumes a visualization where the set of nodes reflecting the main interaction thread are always horizontal with history branches are angled and fanning out over time. Furthermore, gradual transparency is applied highlighting that the nodes are getting older over time.

In the first part of the study, participants performed all the three tasks. In the second part, however, only the Origami and Lego tasks were considered and the abstract representation was omitted towards our focus on exploring different RH design aspects such as transparency, layout, and arrangement.

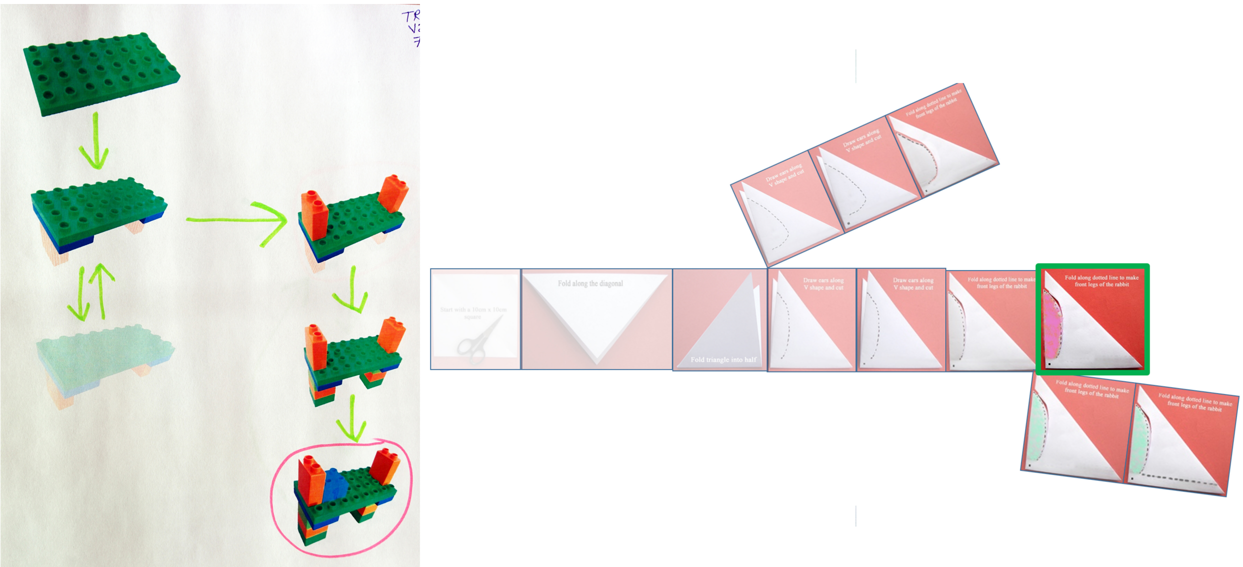


Figure 5.2: Examples of RH design sketches for the Lego and Origami tasks. (Left: a tree where interaction branches are presented with directed arrows and transparency for disregarded paths and with the most recently captured snapshot having a red outline, Right: a transparency-based history visualization highlighting the main interaction branch as always expanding horizontally to the right with disregarded branches fanning out over time)

5.2.3 Results & Discussion

We analyzed the gathered data to understand how participants perceived the nonlinear interaction history representations, and what are their preferences on the RH design variants we explored.

All but two participants responded with "Agree" on a 7-point Likert scale to the statement *"I found the RH representation to be usable for being aware of my interaction over time"*, with the remaining two participants responding with "Strongly Agree" to that statement.

Our content analysis of the data revolved around the following themes, which we argue are important aspects for future design efforts of interaction history representations in spatial tasks: nonlinearity, spatiality, node representation, node connectivity, and usability & usefulness.

NonLinearity

All participants found the RH nonlinear history representations to be useful and preferred them to the abstract one (or the simple undo/redo model). They reasoned that the nonlinear one preserves previous alternative interactions, and provides a clear idea of what have been tried before. The subjective comment from P2, for instance, highlights that, *"I like the possibilities you get with the nonlinear because you can try out several different branches and continue through the one you want. I like that it preserves several paths that you have tried so that you can very clearly essentially switch between three or four different ways of doing the same thing, and choose the one that works best"*. Participants also mentioned other reasons for favoring the nonlinear approach as it: (1) better informs users' understanding of their interaction behavior, (2) simplifies how the interaction history is preserved, and (3) provides freedom for choosing where to jump back in time, without the need to manually trace back the interaction path by performing a sequence of undo(s).

An interesting reflection from one of the participants hinted at the potential of sharing the RH representation with others. That participant gave an example of a teacher who asks a group of students to do some task while logging their interaction history. Then, all the captured interactions are combined in a bigger nonlinear tree, allowing the differences among students' interactions to be quickly identified and all interaction trajectories that led to failure can be re-explained. In this regard, the comment of P6 expressed, *"One thing that can be useful for this nonlinear representation [is] to assign a task to different users and then after a period of time you can check the differences between them"*.

Spatiality

During the first part of this design critique, two out of six participants specifically linked the choice of the history representation to the simplicity/complexity of the task and of one's workflow. Those participants viewed the need for the nonlinear representation with complex spatial tasks while viewing the undo model for simple tasks. In this regard, P3 expressed that the *"Usefulness [of the RH] may not be clear for simple applications, but it is more effective for engineering and modeling"*. Along the same line, P6 expressed, *"this [RH] representation is better for navigation tasks and for being oriented in space, while the abstract graph is better for less spatial tasks like planning things"*.

Node Representation

We gathered participants' feedback on the tree nodes' representation. Only two participants reported that it might be enough to use descriptive text and no visuals especially if the task is non-visual or if the task's real estate is limited. In this regard, P4 expressed *"the text is obviously more compact so that's an advantage, and the other caveat is when you are making changes that are not extremely visual"*. In contrast to having a non-visual node representation, most participants favored a more visual history especially if the task is visual. As P5 commented, *"It is [the RH representation] illustrative of what the actions actually were as opposed to, just maybe, basic node names, so it was easier to recall what the actions were, as well as at a glance see the overall path or the different pathways you took"*. In this regard, the visual nodes are simpler to understand and act as memory triggers for recalling previous user interactions, which is aligned with the comment of P6: *"I prefer [nodes with] graphics because it more easy to follow the history, and you don't have to recreate the history in mind since it is there"*.

Beyond having a 2D image-based node representation, an animated (3D) node could be more helpful, which is in line with the feedback we received from most participants. The responses we gathered highlighted the value of animation to show what has changed especially with complex 3D spatial scenarios wherein just having static image thumbnails may be less expressive. P1 clearly commented about animation saying, *"I am guessing that 3D animated [node] replica would be nice especially if the animation is going to show you what are the parts that took over or what are the parts you added"*. Similarly, P6 stated, *"Yes, it makes sense to use 3D [nodes] because while with the images it may be easy to spot things, some 3D models can be complex and you would need to rotate to see the different part of it, which you can't do with the images"*.

Transparency is an interesting concept that could be applied to tree nodes (and branches) to simplify reading the tree and to hint at the temporality of user's actions. However, feedback from participants was not conclusive regarding the usage of transparency. Most participants understood that making disregarded branches (or nodes) transparent reflects that they are gone and that it is not possible to interact with them anymore. Furthermore, many participants suggested applying transparency to the design of nodes with a constant value and to not dynamically fade it over time. As P2, for instance, described it, *"I like the transparency but I like it as a clue that you are not here anymore ... When I see transparency fading, i see that I cannot go back to that point any more"*. Alternatively, P3 suggested to vary the effect of time on nodes with a gray-scale rendering (instead of transparency) to avoid confusion, leaving recent nodes vivid and with older ones losing color, so it is easier to see what have been done. This effect is only about making history nodes less colorful, and not to be confused with the design that intends to make some of the user interface elements disabled by graying them out. In essence, most participants agreed that transparency could be helpful, but stressed that it should be carefully utilized (e.g., by applying it consistently to nodes as opposed to having it fade over time).

We envision flexible RH representation that adapts to immersive environments with the rich variety of sensory elements that may exist (e.g., visual, sound, tactile). We gathered participants' thoughts on whether it would be useful for the RH node representation to include logging of such additional sensory elements. While many participants found it difficult to imagine integrating additional sensory information in the node representation, almost half of them stated that it could work especially in complex simulation environments. They stressed, however, that it should be dependent on the task to avoid confusion, and that the designer should be selective or at least eliminate such information that would not be helpful. The following comment of P3 is among those who favored the idea, *"So you are basically planning to capture the whole experience ultimately ... I would say I do not see it being done any other way. With only the visual image, you need some time to figure out if this is where you wanna go back to, but with the entire experience, you just need a little bit"*. Here, potentially useful is to have audio tags acting as memory aids that remind of when and why an action had happened. P1 gave an example related to writing by saying, *"I think having audio tags would be nice, for example, when writing something with lots of edits, I mean, it goes beyond just these changes, and it is the more information about why it happened"*.

Some participants raised a concern for nonlinear tree-like representations as they get very big while logging many actions. As P5 wondered, *"I don't know if it is gonna be a problem when you have many [history] threads of different actions, [for instance] may be in a more exploratory scenario when someone is trying many different things"*. We argue that almost all history representations, whether linear or not, would be less usable if many user actions were logged. Imagine having a very long list of history actions, it would be difficult to scroll through them to find where to jump back in time. We believe that, in many scenarios, only subset of user's actions need to be saved as most people care about specific interaction moments or only the recent ones. In scenarios where large interaction history is logged, some techniques can be used to simplify this issue including combining certain nodes/branches, utilizing transparency, and providing search/filter capabilities.

Node Connectivity

Different rendering styles exist as possible options for connecting tree nodes. These include having explicit lines (e.g., solid, dotted) with varying thickness as well as with the option of directly attaching nodes to each other, effectively connecting them without any lines at all.

Participants' opinions on line connectivity varied. Only two found lines unnecessary as they can get in the way and that the sequence of history nodes is still clear without them. The remaining participants, however, preferred having some sort of line connectivity especially if the representation layout would change dramatically. Those participants added that lines should be dotted, thinner, or transparent for disregarded branches and should be solid, opaque, or thicker for the active path. In this regard, P6 said, *"Lines should be dotted for the path that you skipped and strong one for the current path, because here you would have a clear visualization of where you are. And you have to have lines [between nodes]"*.

Some participants mentioned that line segments should be directed (with arrows) for clarity and to guide the layout especially if the representation does not have implicit arrangement (e.g., root's location is not fixed). Tagging nodes can also simplify the lack of implicit arrangement (e.g., with text that indicates event ordering). P1 described this by saying, *"Definitely, you could have a dynamic time [tag], or a number, or if you always indicate what is the starting point, then people can read because you always go from top to bottom or from left to right"*.

Usability & Usefulness

All participants agreed on the usefulness and usability of the RH representation, especially with correct encoding. As P4 puts it, *"It is useful to see the task context during temporal interaction. With the abstract [graph], it is hard to remember what all these actions were"*. Another participant highlighted that correct visual encoding is important to the usefulness of representation (e.g., careful choice of colors, size, layout, and transparency).

Interestingly, P1 mentioned surgical simulation as a scenario that could benefit from the RH representation where doctors can try actions while maintaining awareness of the things that could go wrong, ultimately to enhance their learning. Finally, intuitive interaction with the RH representation is needed for better usability. Most participants mentioned that they would prefer having flexibility when interacting with the RH representation (e.g., the ability to change its location, zoom it, or save/restore it as needed). For instance, P3 stated that *"The placement of [the RH] representation should be [in] separate [window] because the amount of work you do with it is not little"*. It is also worth noting that most participants were less excited concerning utilizing other interaction modalities including speech when interacting with the RH representation.

Preference for the RH Design Variants

One of the goals of this study was to gather participants' preferences regarding the provided RH representation's design variants, which we explored in the second part of the study for each of the study tasks. For the Lego task, four out of six participants preferred the RH design variant that utilizes transparency for the disregarded nodes/branches. Reasons for favoring this preference included giving better impression of time, clarity, and avoiding repetition. For instance, P6 commented *"I prefer the one with transparent branches because visually it is much more clear, while the other one looks a little bit busy"*. Concerning the RH variants that have been used with the

Origami task, four out of six participants preferred the RH variant involving a tree-like organized structure that doesn't have gradual transparency. These four participants provided reasons that revolve around layout flexibility and clarity. For example, P4 expressed: *"Using the column/row format [of this RH design] is less cluttered. I like the more structured approach as it is clear and easier to go back in time [with it] especially if it is animated and balanced"*. The other two participants favored the second RH variant, which utilizes gradual transparency and a horizontal main thread, due to its utility for conserving space with its straight (horizontal) path and the dispensing of node connections.

Some participants also provided suggestions that are applicable to all design variants of the RH representation. For instance, P4 suggested collapsing the less important tree nodes to avoid having a gigantic tree representation over time. He or she also added that textual tags can be integrated with graphical nodes, but it does not need to be included with all nodes to help conserving real estate (e.g., the context space). Another participant, P5, explained that it might not be necessary for the RH to highlight where you are in the tree because it can be seen in the model (or the current interaction context), and that only the history nodes need to be shown.

5.3 Applying ReflectiveHUD in Simulation

Based on the insight from our previous design study, we explored preliminary implementation of the RH representation within a spatial immersive surgical simulation prototype, which we named ReflectiveSpineVR. The developed prototype intuitively integrates interaction history capabilities that support repetitive practice and aims to contribute better training and learning (Figure 5.3). In this work, we only focused on applying the RH representation within a surgical simulation scenario, but we argue that it can be applied to other immersive contexts, especially those that are spatially rich and which potentially benefit from logging user actions over time.

ReflectiveSpineVR focuses on simulating the procedure of pedicle screw insertion and supports visualization of the spine and its context utilizing fully immersive rendering and 3D haptic

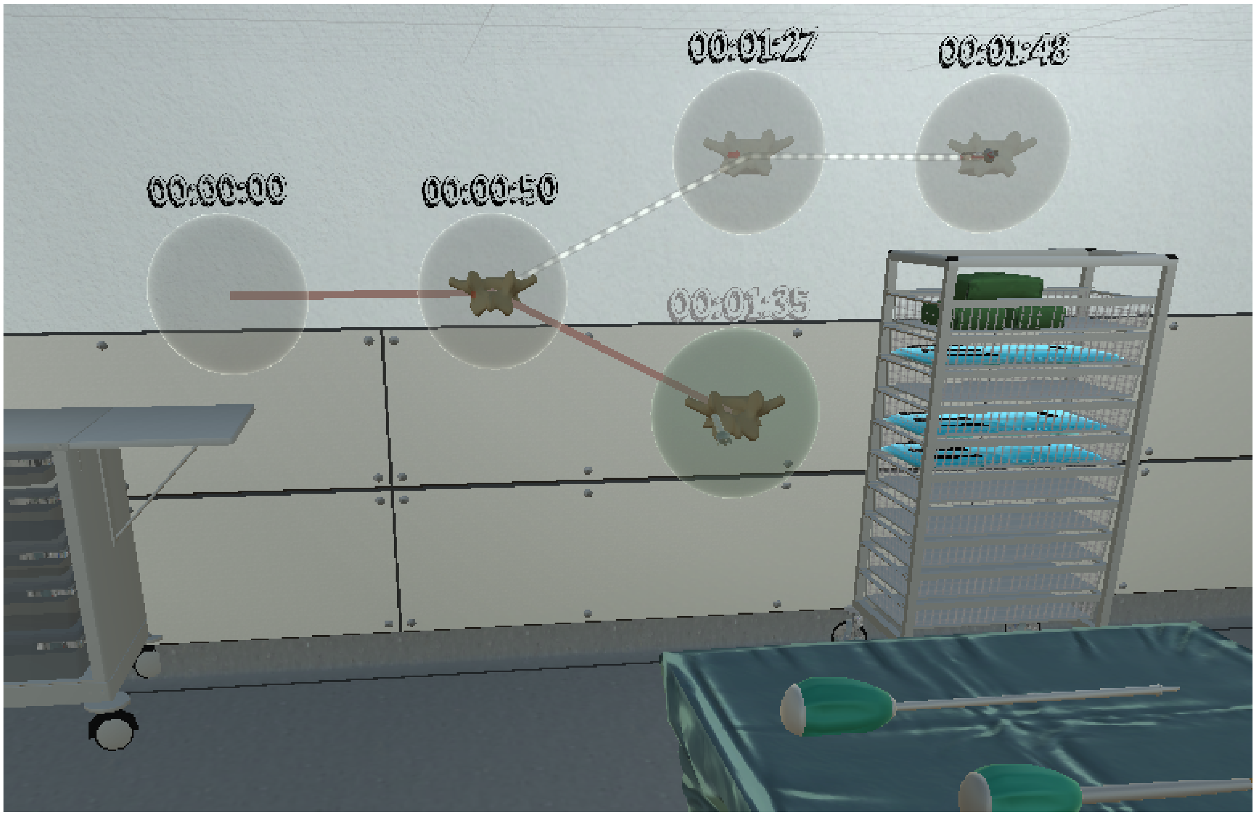


Figure 5.3: A view of the immersive surgical simulation prototype showing the ReflectiveHUD tree floating in the virtual 3D space.

interface capabilities. The virtual reality simulated context consists of a semi-realistic replica of the surgical operating room (OR), which was developed following consultations with our medical expert collaborators (Figure 5.4).

5.3.1 Design

Prior to integrating the RH representation within ReflectiveSpineVR, we discussed the findings of the design study with our medical collaborators. We followed a participatory design approach [205] wherein the medical experts participated and agreed on what the history visualization would look like. The design process was iterative and was continuously guided by feedback from our medical expert collaborators.

We made various decisions when designing the RH visualization. First, and because of the spatial richness of this context, we decided to visualize the RH representation as a floating tree in the 3D simulated space allowing the user to look and interact with it as needed. The position of the root node is always fixed within the 3D virtual space, but it can be customized as needed.

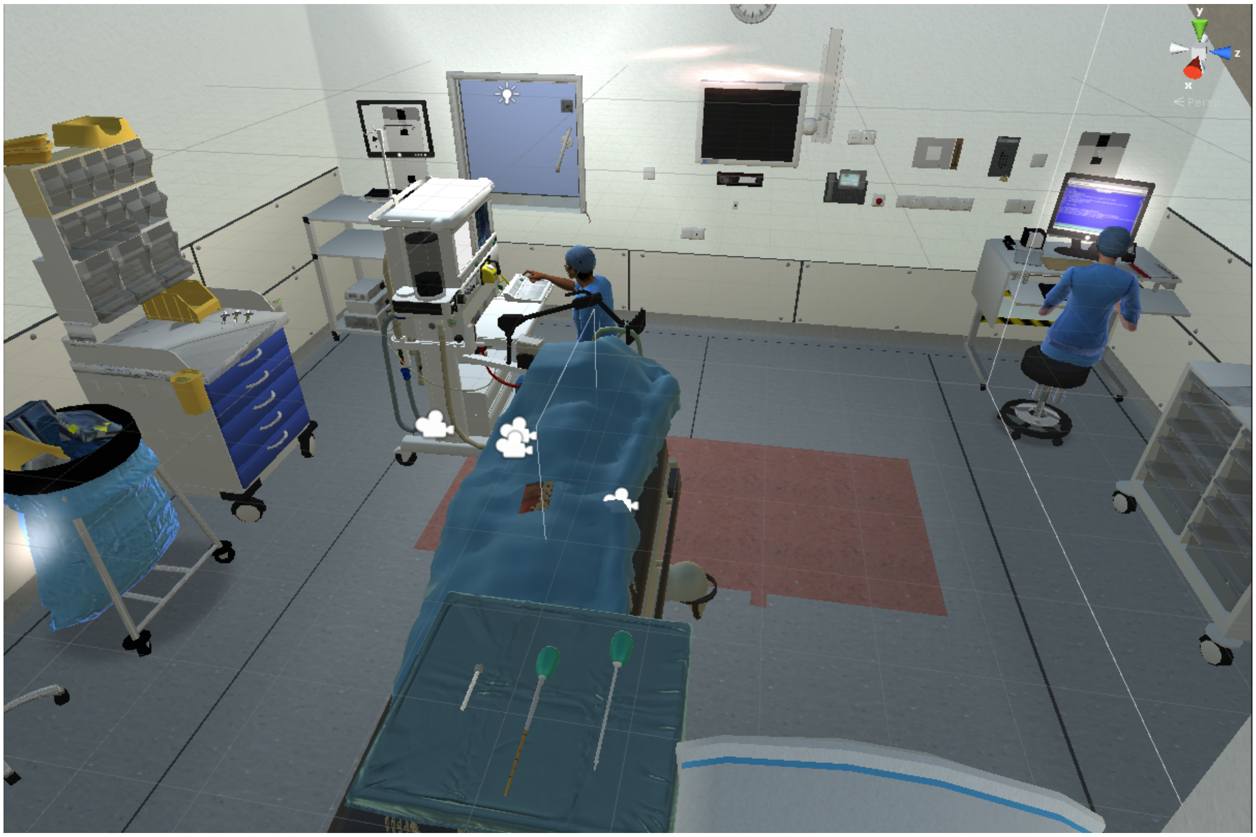


Figure 5.4: The immersive surgical simulation context resembling a replica of an actual operating room.

Animation was a key part of the RH representation. For instance, when a new node is added (i.e., when the tree is growing), the tree layout is animated to make room for the new node, so that the tree presentation is always balanced and optimizes the view estate. It is worth noting that this animation only affects the surrounding nodes (e.g., sibling, parent, children) of the one being added to avoid confusing the user, which might happen when the whole tree layout is manipulated.

We represented each node in the RH visualization as a semi-transparent 3D bubble. The inside of each bubble reflects a preview of the logged user action saved as a snapshot of what occurred at that moment. In our simulation, for instance, if the user interacts with a specific spine vertebra by drilling its bone, this action including the modified object will be cloned inside the transparent RH bubble (Figure 5.5). For clarity purposes and due to the similarity of some user actions, supplementary textual tags may be beneficial. In this regard, we render 3D text that is displayed above each tree node, which by default reflects the time of the action that occurred but it can be customized as needed (e.g., the name of each spine level). We also decided to vary the rendering of the currently selected/highlighted bubble, by making it slightly bigger than other nodes, tint it with different color, and highlight its textual tag. Finally, we decided to automatically re-orient each bubble's content to always face the camera, which would make it easier to see the 3D content inside the tree nodes. An alternative approach would be to allow the user to explicitly manipulate each bubble's content, but this idea merits itself as an interesting future work.

We decided to make the connection between nodes in the active path (from the root of the tree to current node) using solid lines while rendering the disregarded paths (the previously tried paths) using dotted lines. Furthermore, the active path connections were colored dark red while the inactive paths were white (Figure 5.3). In essence, the goal of this design is to quickly hint the user at the current temporal interaction thread and distinguish it from other (disregarded) history paths.

We utilized the haptic hand controller to enable interaction both with the virtual patient and the tree presentation. In particular, we designed a tree-interaction mode, which can be activated when the user presses a specific button on the haptic arm. In this mode, a virtual ray is displayed from the user's eye allowing the user to point at and interact with the tree nodes. The user, then, can use the other haptic buttons in the haptic controller to restore the simulation to a particular selected node.

When a user decides to jump back in time to a particular node in the RH tree, we activate a transitioning effect by blurring the camera's rendering, animating its field of view, and by presenting everything in grayscale. Also, a sound effect is employed, hinting to the user that he or she is travelling through time. It is worth noting that we have experimented with a variety of other effects before reaching a final decision for the aforementioned transitioning effect.

In essence, the design and integration of the RH representation within our simulation prototype enable users to save their interaction progress and to jump back in time to a previously saved snapshot, effectively resetting the simulation to that moment.

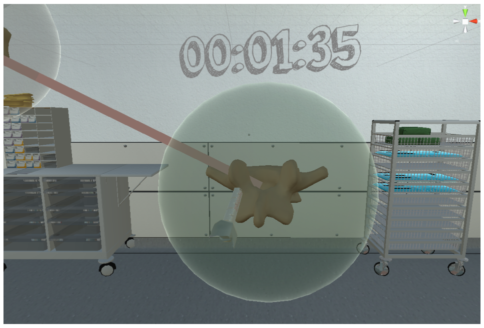


Figure 5.5: A ReflectiveHUD tree node tagged by action time, and shows a spine vertebrae with a screw inserted in it.

5.3.2 Hardware and software

ReflectiveSpineVR supports 3D stereoscopic rendering as well as auditory and haptic feedback for user interaction. We used Unity3D as our prototyping environment with the Oculus Rift [67] CV1 and the Touch Stylus [222] hand controller for supporting haptic feedback. The Touch Stylus was integrated using a Unity plug-in that utilized the well-known OpenHaptics library [81]. The computer we used had a Nvidia GTX 980 graphics card with a 24 inch monitor that was able to provide a 60 Hz refresh rate consistently at the native resolution of 1920 by 1200 while running the simulation in Unity.

Our simulated virtual world included a semi-realistic representation of an actual surgical operating room (OR) including 3D patient model (obtained from the Lindsay project at the University of Calgary [174]) lying on a table in front of the user and variety of medical devices and tools (Figure 5.4). During the simulation, a pulsing OR sound is continuously playing in the background as a way to increase the level of immersion. To simplify user interaction with the medical tools and the RH tree representation, we utilized the RayCasting interaction technique [22]. In this regard, we render a selection sphere guided by user's head that is only visible when the user looks at specific areas (e.g., the table that contain the surgical tools). Once the user's look direction hits an interactable object (e.g., one of the surgical tools) within the immersive environment, the rendering of that object will temporarily change to afford interaction (as shown in Figure 5.6).

Our implementation involved various C# scripts handling the different features of the simulation. In this part, we refer to the main scripts for rendering and handling the haptic feedback. Visualizing the 3D immersive environment involved modules for rendering the interaction ray, the post processing effects, the automatic alignment of the camera view, the rendering of the ReflectiveHUD tree, and some CG shader programs for the x-ray effect and applying selective transparency to any 3D object. The haptic feedback was achieved through a set of scripts that initialize the external haptics library, match the Unity collision detection features to the haptics library and vice versa, and enable manipulation of the haptics properties, as needed. In addition to the aforementioned core rendering haptics scripts, some code was responsible for updating the GUI and the interaction flow.

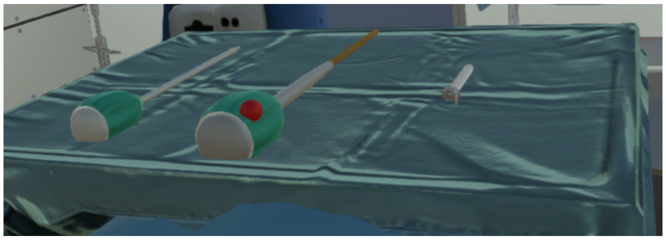


Figure 5.6: A surgical tool is rendered slightly bigger when the user looks at it using his or her look direction.

5.4 Evaluation

We conducted a preliminary evaluation, gathering feedback on how our participants perceived the RH representation and the overall immersive experience. We hypothesized that our temporospatial RH representation would be effective for raising awareness of user's interaction history within immersive simulation, and would support repetitive practice and the overall learning experience. Our participants experienced the simulation of a simplified surgical task augmented by our implementation of the RH representation. All the recruited medical residents and surgeons provided positive feedback about the immersive simulation and the RH representation, highlighting its potential for supporting repetitive practice and medical education especially for novice people.

5.4.1 Participants

The participants of our study involved 6 medical residents and surgeons (5 M / 1 F) of varying expertise (junior and senior) who tried the simulation and provided feedback. We acknowledge the difficulty in recruiting large number of subject matter experts who are often busy or unavailable for such studies, and highlight that we managed to recruit participants representing more than half of the existing residency program.

5.4.2 Study Design & Procedure

We had two pilots in addition to our study participants; one with a surgeon staff member and the other with a junior resident. The outcome of these pilots contributed to improving our simulation prototype prior to conducting our study.

At the beginning of each study session, participants were introduced to the concept of interaction history and the ability to manipulate it using the undo/redo features of the Microsoft Word application. Afterwards, participants received training of the simulation and its usage including how to utilize the RH history representation. Then, each participant was asked to use the immersive simulation by following a scripted PSI task. After going through the immersive experience, each participant completed the iGroup presence questionnaire (IPQ) [204], which we choose because the author's definition of presence corresponds with our own; the subjective sense of being in a virtual environment. Examples of the IPQ items are: *"I felt like I was just perceiving pictures"*, *"In the computer generated world I had a sense of "being there"*, and *"I still paid attention to the real environment"*. Each of the 14 IPQ items follows a 7-point scale resulting in potential presence values between 14 (minimum) and 98 (maximum). Finally, the participants completed a short usability survey (5 questions) and a post-study interview (7 questions) after the IPQ questionnaire. In this last part, participants rated their satisfaction with the simulator and reported on what they thought are the useful features or limitations of the simulation including how realistic the visual/haptic feedback aspects were. Our participants also commented on different aspects that relate to the RH history representation including their preference of the RH approach versus the linear history model and how they perceive the value of RH for supporting repetitive learning. The duration of each study session lasted less than one hour.

The scripted task used in this study utilized the simulation environment to educate users about the task of pedicle screw insertion. Each participant was asked to imagine himself/herself as a junior/novice medical student who knows very little about the procedure of pedicle screw insertion, and that he or she is doing it for the first time. In this regard, the simulation task involved the core procedure steps (e.g., identifying a landmark, drilling a pilot hole, and inserting the screw) as well as few additional steps reflecting the unexpected threads where things could go wrong (e.g., having less optimal landmark placement, touching the nerve, or making a breach by going through the bone).

5.5 Results & Discussion

The prototyping of ReflectiveSpineVR went through multiple iterations guided by feedback from our medical collaborators. Our immersive prototype enriched with interaction-history features enable surgical trainees, especially the novice ones, to learn about and repeatedly practice the PSI task. As one of the medical participants stated, *"The ability to try a step in a vertebrae multiple times was really valuable for mastering [this surgical skill] especially at my current novice level"* [P5]. Such a feedback reflects on the RH potential for supporting repetitive practice and skill training, enriching the overall learning experience.

In this part, we report the study results that relate to how our participants perceived the immersive environment as well as their reaction to the simulation features including the RH visualization.

5.5.1 Presence

Our participants have positively experienced our immersive simulation, and this insight is supported by the results of the IPQ presence questionnaire and the qualitative responses received. As we only had a relatively small sample size of participants, we refrain from making any statistical significance claims.

We analyzed the presence data in two ways. First, we calculated an overall presence score for each participant as shown in Figure 5.7. This result highlights that all participants felt somehow present within our immersive simulation (Mean score = 64, STD = 4.7). Second, we attempted to group the data from all participants for each of the unique IPQ items, reflecting on the testing of general and spatial presence, the experienced realism and how each participant felt involved within the immersive environment (Figure 5.8). While this result highlights that our participants experienced less simulation realism, we argue that it may be because they expected better haptic feedback, which was not the case in this simulation since our focus was on the interaction history capabilities. This interpretation may be seen from the comment of P2 when he or she expressed, *"The haptics are not the same compared to real life; [I] couldn't adjust the pedicle finder [tool] after engaging the bone"*.

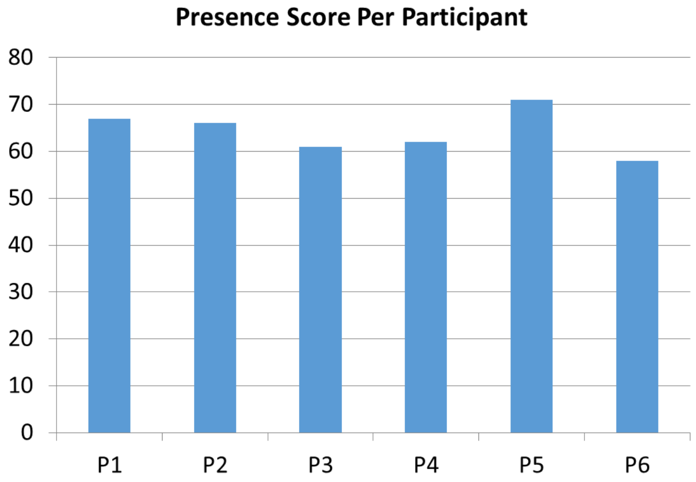


Figure 5.7: Presence scores per participant combining all the IPQ questionnaire items.

We received many subjective comments from almost all participants highlighting how they liked the immersive environment. For instance, P1 expressed, *"The ability to be immersed in the virtual world significantly adds to the learning experience"*. Another participant, P4, commented on how our virtual world simulated the real experience well, when he or she said: *"One thing I did like about this simulation, is that the fluoro [x-ray] is in a place where you can see it in the operating room when you look up, so that by having the tree next to it, kind of adding to that hub of accessory of information in front of you; all in one place make sense and it is less distracting. I do not foresee in better position"*. These feedback reflect the importance and value of supporting immersion and having good replication of the simulated context. Indeed, the effective design of immersive simulation contribute to mediating experiential learning in such interactive learning context.

5.5.2 Simulator's Usability

All participants reported high satisfaction with our simulation, found its visualization to be quite realistic, and liked its simple interaction (Figure 5.9). The qualitiative feedback we received support this conclusion. As P5 puts it, *"The interface of the system is very easy to use and is user friendly"*. Similarly, P6 expressed, *"The re-do part [referring to the RH] was easy to access and easy to do"*.

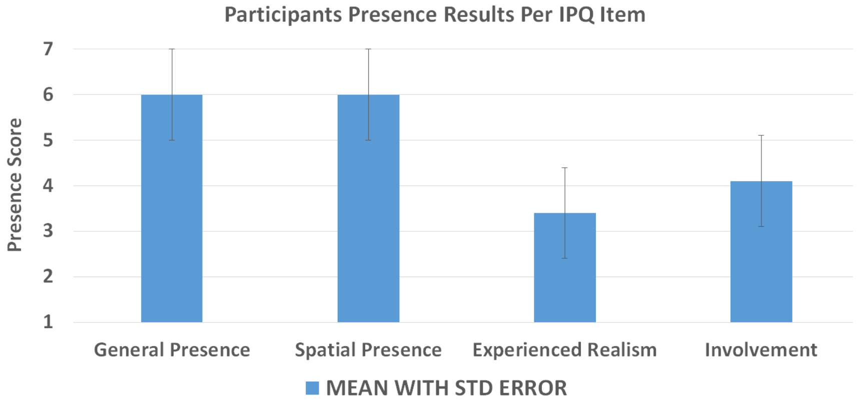


Figure 5.8: The Mean of IPQ Presence results grouped per category for all participants

All participants were able to effectively interact with our simulation and the RH representation.

For instance, P1, commented on the idea of interaction guided by head direction, *"I think the way you have it is very intuitive and I was able to learn rapidly with minimal instruction"*. We also received positive feedback with regards to our visualization. For instance, as P6 puts it, *"The feedback of imaging from the computer were extremely useful to see where the screws were put"*. More specifically, for example, our choice of rendering the RH branches as dotted/solid paths seems to make sense. The example comment from P5 reflects that when he or she said, *"it was cool, very intuitive, and yea it just made the tree very useful"*. These reported comments confirm the importance of following usability guidelines when designing interactive simulation systems, and how this facilitate usage and interaction with the immersive simulation.

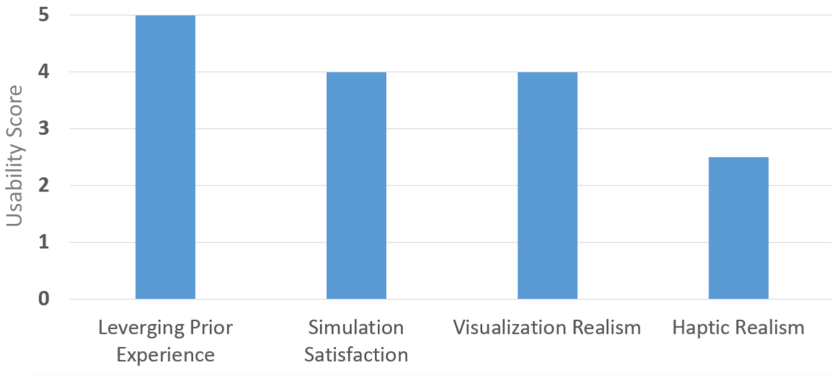


Figure 5.9: Participants' usability responses for our prototype (higher is better)

We also received feedback about the simulator's limitations as well as suggestions for improving it. Examples of aspects for improving our prototype included tagging the tree nodes with more descriptive text and considering ways to handle quickly growing tree branches. For instance, P5 expressed, *"You may have tree that is very long, say you are not doing like a three-step operation, say you are doing like the full thing [with more steps and repeatedly with multiple screws], you may have to come up with some way to collapse and expand the branches"*. The key limitation as reported by various participants relates to the haptic feedback that seemed less realistic. For instance, P1 expressed, *"The haptic feedback is good, but if people were to use it to improve their skills then it needs to be more realistic"*. Indeed, we did not focus on having accurate haptic feedback on our implementation since it would require complex integration that is beyond the focus of this research. This concern of the poor haptic feedback can be mitigated in future work either by improving the haptic implementation or by using better haptic devices.

5.5.3 History Representation

Our participants reacted positively to the interaction history feature we integrated. Two thirds of our participants responded with "Strongly Agree" to the following statement, *"I found the history tree representation to be useful for being aware of my interaction within the simulation"*. The remaining participants answered with "Agree", using the 7-point Likert scale we used.

The positive results we received about our history representation were supported by many qualitative comments. First, with regards to supporting temporal interaction, P5 stated, *"I think this [RH] gives you more flexibility, like, if you instead of a screw being 3 steps, it is 10 steps, it would take 10 clicks to go back to the beginning of the whole sequence, whereas with this [approach] you can pick exactly how far you want to go back in one click"*. Along the same line, P6 said, *"I prefer the one that you made [over a simple undo] because it is more visual and because we are doing a simulation for something actually visual and by having the visualization it just reminds better your memory what has been done before"*.

Many of our participants highlighted the potential value of the RH representation for supporting planning and learning. As one participant said, *"I think this [RH] is better [than a simple undo] because it gives me the ability to review what I did wrong ... If I make multiple attempts, just the simple linear undo/redo won't give me the chance to branch and see what I did before. So, from a learning perspective, this is definitely more useful"*. Similarly, P1 stated, *"I think the trajectory planning [for the screw insertion task] is quite good with this tree"*. Along the same line, P4 stated, *"I think the nonlinear way presented in this simulation is definitely superior [to a simple undo], especially with pedicle screw [task]"*. These comments reflect on how the "non-linearity" inherent in the RH representation has the potential to support learning.

Finally, we present two interesting comments of how the RH representation can be shared with others and how it is perceived as potential addition to surgical simulation. First, P5 highlighted how the RH may be used to reinforce learning at situations of failure, when he or she stated, *"In terms of learning, it is interesting, cause it is like a lot of your previous steps, so if you landmarked poorly and you saved [your progress with the RH] after your landmarked, your teacher can come by [look at your interaction tree] and show you where the thing that made everything else goes off"*. P4 who tried other simulators commented saying, *"I think this tree addition is very big asset because in the other ones you have to restart from scratch, and for me one of the important aspects of learning is the fact you can use sub-optimal placement of your screws and then learn how the different trajectory may affect your outcome whereas in other simulations if you put that ill-position landmark you have got one shot of trying to fix it, or you would have to restart the simulation trying to get better at the same ill-positioned before you can give it a go. I think you learn a lot more form that instead of trying to do the full thing from scratch"*.

It is noteworthy that the results of our evaluation, in part, may reflect the success of our simulator in achieving face and content validity [142]. However, because we focused on the assessment of user experience aspects including immersion and repetitive practice, we call for a new type of assessment that we named experience validity, extending existing surgical-simulation validation measures.

In summary, our results highlight the benefits of empowering users with interaction history features, which would enable reflection, repetitive practice and learning from own mistakes. Accordingly, we encourage designers of immersive systems to consider and integrate effective history visualizations in their designs. We argue that our suggestion reflects a unique learning aid that has the potential to mediate experiential learning in such immersive environments.

5.6 Conclusion & Future Work

We proposed ReflectiveSpineVR, an immersive 3D spine simulation enriched with interaction history capabilities to enable repetitive practice and aid education of surgical procedures. We consider the proposed interaction history visualization a unique learning aid that empowers learners' memories and enables deliberate practice towards mediating experiential learning in immersive surgical simulation contexts. The conception and integration of our interaction history representation were guided by the insight we gained from a design study we conducted prior to developing ReflectiveSpineVR. Also, our research process involved collaboration with medical experts through various iterations to meet their expectations and needs. We presented a preliminary evaluation highlighting the potential benefits of integrating spatial interaction history representations in an immersive surgical simulation environment.

ReflectiveSpineVR is the first immersive prototype where we explored our interaction history ideas, and it can benefit from specific improvements. In particular, the feedback we received can be considered to refine our implementation. This includes changing the representation of specific tree branches to be more compact once the history visualization tree grow beyond certain limit in order to simplify its exploration. Also, the proposed interaction history representation should be integrated into other immersive simulation scenarios with formal studies. This would confirm more accurately the practical value of such representation for supporting temporal interaction and simulation-based education.

Chapter 6

Designing JackVR: An Immersive Training Simulation for Landing Oil Rigs

In this chapter, we build on inspirations from games and the Superhumans metaphor [155] to support the training of landing oil rigs. We propose JackVR, an interactive immersive simulation prototype aiming to train domain experts to land jackup oil rigs. Our design of JackVR explores various superimposed spatial indicators and gamified visual warnings on unexpected task conditions. The implemented prototype supports two modes for training, and utilizes the ray-casting interaction technique to enable seamless and direct control of the rig. It is worth noting that parts of the work presented in this chapter has appeared in the following publications [161].

6.1 Introduction

Virtual reality (VR) training applications are widely used to prepare users for tasks that may be too costly or dangerous to practice in real world settings [186]. Within the oil-and-gas domain, some VR training systems were proposed and implemented in order to support domain experts who train for challenging oil-and-gas processes and tasks (e.g. [66]).

One such task, which is the focus of this chapter, is the process of landing a jackup oil rig. This process involves many environmental challenges including unpredictable weather conditions, varying (deep) ocean forces, and uneven seabed topography. During the landing process operators are provided with a simplified user interface to control the oil rig (e.g., move its legs up/down) with minimal visual feedback, which is arguably insufficient to satisfy the complete set of task requirements. During the landing the operator must stably and correctly position the rig to previously defined positions at the seabed, while being aware of dynamically changing environmental conditions, and carefully avoiding risks of damaging the topography of the seabed. These challenges motivated the design of JackVR, a training system that provides domain users with an immersive environment that helps them understand the multifaceted challenges of landing the oil rig, and practice landing it in a semi-realistic experiential environment.

Bin He [94] proposed a virtual prototyping system to validate the design of an offshore drilling platform including its jacking systems. However, to our knowledge, there is no immersive system that supports practicing offshore oil rig landing.

We propose JackVR, an interactive training system that supports domain experts train in landing jackup oil rigs in a variety of simulated scenarios. We implemented JackVR as an immersive virtual reality simulation of jackup oil rig landing. Our prototype takes inspirations from the Superhumans metaphor [155] and integrates gamification aspects in its design. This enables domain users to fully control various environmental simulated conditions such as ocean waves and wind, and also supports spatial interaction using the ray-casting interaction technique (Figures 6.1, 6.6). In this chapter, we detail the main components of JackVR, its usage in landing simulation tasks, and our plans for future improvements. It is worth noting to highlight that my role in this project involved the actual design, implementation, and evaluation of the simulation prototype. It also included drafting the project report for publication.

6.2 Jackup Rigs

Jackup rigs [189] are among the most common offshore drilling units that aid in the process of hydrocarbon extractions. A jackup rig usually consists of the rig itself, the legs, spud cans (heavy objects attached to the legs to facilitate seabed penetration), and the hull. For more information about Oil Rigs and their structure, we suggest referring to Appenidx A.

Many steps are associated with the operation of landing a jackup rig (Figure 6.2). The jackup rig is pulled (moved and oriented) to the target location usually by a couple of ships. Then, the jacking system is used to lower the legs with careful attention to the environmental forces and the

Figure 6.1: JackVR's Concept: immersive landing of oil rigs with Ray selection technique

seabed depth until the legs touch the seabed. Next, the hull is raised out of the water prior to filling it with water to increase the total weight of the rig, in order to enable penetration of the seabed. Following the penetration, the hull is further raised leaving an air gap for more stability, with the rig fully landed and almost ready as a fixed platform for drilling. JackVR supports practicing all the landing phases with the exception of the pulling to the target location (the 1st phase), which reflects on towage task components that are arguably external to the core landing process.

6.2.1 Why JackVR?

Operators of oil rigs may need to control the rig through a simplified desktop interface that only supports basic interaction capabilities to land the rig along with standard 2D images of the under-ocean terrain topography. Due to the apparent lack of simulating the surrounding environment, a more realistic, experiential, safe, and engaging training environment is needed to better educate the operators about landing the oil rig, especially with the various weather and environmental challenging conditions. In this project, we propose JackVR, an immersive simulation and semi-

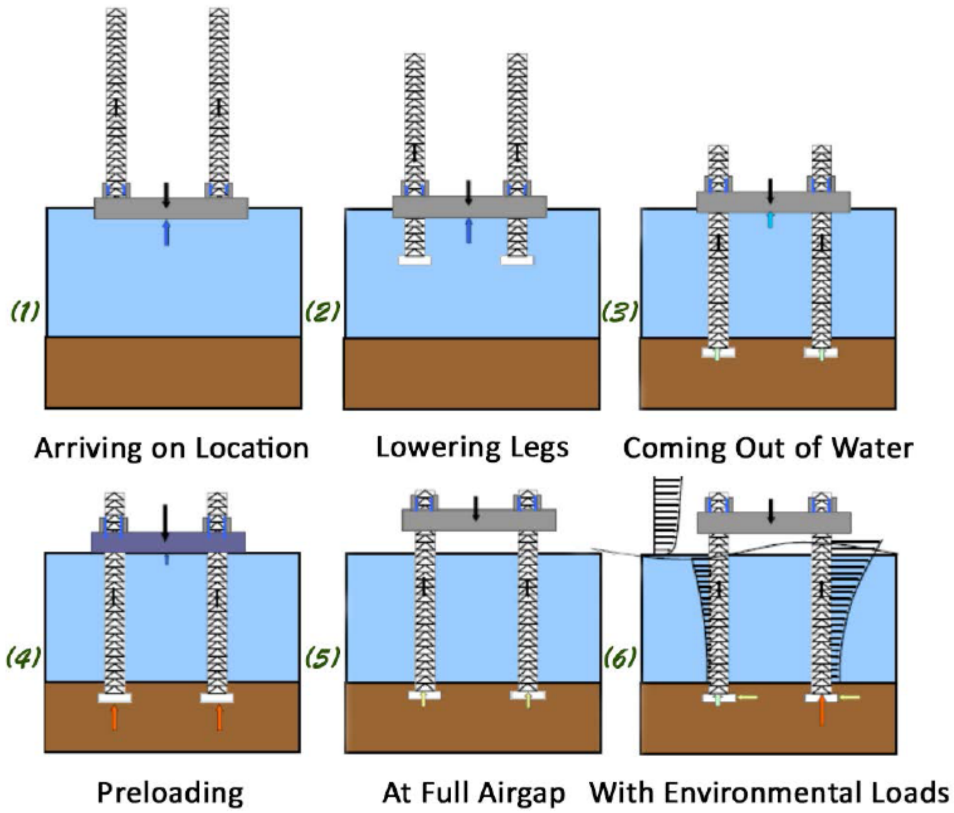


Figure 6.2: Steps involved in the process of landing jackup oil rigs.

realistic experiential training environment for the process of landing oil rigs. In our early meetings and consultations with our domain collaborators, they highlighted the importance and potential of having an immersive environment, such as JackVR, to support the training of landing oil rig.

6.3 Methodology and Task Design

The design of JackVR followed an iterative methodology [207], based on feedback from domain expert collaborators. We decided to design our prototype allowing users to experience two training modes, "normal" mode, and what we termed a "superhuman" mode. This decision was inspired by the Superhumans metaphor B, which encourages designers to consider a set of super-humans capabilities in order to empower end-users within the immersive environment.

When the normal-mode is set, users are able to completely control all aspects of the training with the same low level of insight that can be expected from the current oil rig landing interfaces. While in the “normal” mode, the visualization is lacking and only few low-level insights can be gained. It is worth noting that domain experts often resist learning and trying new tools (e.g., [154]). By including the more familiar normal mode, we anticipate a simpler transition to learning and adapting the new, superhuman, mode.

The “superhuman” mode would allow users to explore intuitive interactions directly as additional features provided over the simpler “normal” mode. We decided to adapt gamification for our implementation of the “superhuman” mode. This enables the users to benefit from empowerment of “supervision” abilities and intuitive feedback including superimposed gamified visualizations of the simulation and awareness of the surrounding objects in the environment. Furthermore, the superhuman mode has potential to extend users’ engagement beyond the use of natural interaction techniques, with a vision for future use of drones (or small submarines) that would aid in such complex simulation processes. In essence, this unrealistic mode provides a more engaging experience and better understanding of the simulation process and its various attributes, with the goal of enabling rich task awareness and as a result better and more efficient training and learning experience.

6.3.1 Simulation Attributes

The design of JackVR simulation included the following simulation elements: (1) a module that simulates the environmental forces, (2) a notification and warning messages generation module, (3) a state-machine module that continuously evaluates the possible outcome of the training, and (4) interactive visualization module which renders the 3D rig model and supports the various spatial VR interactive techniques.

JackVR continuously simulates the environmental conditions impact on the rig’s tilt and movement. We use simplified physics simulation with two parameters that affect the rig tilt, ocean condition and depth, as a simplified representation of any horizontal or vertical environmental forces such as wave current and hull weight. We assume that the sea condition is the main (angular) variation that affects tilting the rig. We modeled this parameter using a simplified 1D noise function to

		Seabed terrain topography	
		Smooth	**Rough**
Sea Condition	**Calm**	Easy	Normal
	Normal	Normal	Hard
	Stormy	Hard	Very Hard

Figure 6.3: Training difficulty levels.

provide randomness in a controlled way (as opposed to uncontrolled random values from typical random-number-generators). The output from the noise function is a random angle that is generated periodically as the new rig orientation, and is interpolated over time to smoothly reflect the new tilt status. Ocean depth is the secondary parameter that affects the tilt according to the current depth of the rig's legs. When the legs arrive at the seabed, we consider the internal rig weight to be at the highest and stop the tilt motion. It is worth noting that our modeling of these simulated parameters was ad-hoc and may not reflect an accurate representation of the rig behaviour and the environmental physics. In this regard, we argue that our simplified model is semi-realistic and that it can easily benefit from actual data if available.

If	**Easy**	**Then**	**Failure never occurs**
If	**Normal**	**Then**	**Failure if mistakes ¿ 2**
If	**Hard**	**Then**	**Failure if mistakes ¿ 1**
If	**Very Hard**	**Then**	**Failure for any mistake**

Figure 6.4: Training outcome according to JackVR difficulty levels.

The warning messages module is integrated as a visual notification reporting the status of the landing. A warning value is issued by continuously taking into account the following simulation parameters: sea wave conditions (e.g. calm, normal, or stormy), the depth of the rig's legs relative to the total depth of the ocean floor, the status of the hull (either raised or lowered), and the type of the seabed terrain topography (either smooth or rough). We designed the warning notifications to allow trainees that miss early notifications continuous indication of the simulation status and better chances of recovering from problems that might have been ignored initially.

A state-machine component was designed to continuously evaluate the overall simulation status, and determine landing success or failure. Prior to the simulation start, the user customizes a set of parameters that determine the difficulty level, which is later translated into a set of simulation variables (Table 6.3). This customization phase allow the simulation to better fit the varying expertise of potential users. Afterwards, the training outcome is evaluated based on the simulation difficulty level in combination with the total number of users' errors (Table 6.4). For instance, in the 'very hard' difficulty level the user can fail the entire task if the rig's hull is raised in the VR immersive environment earlier than it should.

Figure 6.5: Landing a jackup oil rig with JackVR

6.4 Implementation

The visual user interface of JackVR was designed to be rendered in stereo head-mounted display (HMD). We used the first Oculus Rift device (DK1) with a computer empowered by a Nvidia GTX 980 and a 24 inch screen running at the native resolution of 1920 by 1200. We also used a wireless

XboX controller that was configured to work with Unity 3D. For rendering many of graphical effects, we leveraged the rich freely availabe plug-ins at the Unity store (i.e., for rendering 3D waves). Our visualization utilized the integration of Oculus VR SDK (OVR v0.2.5) for direct rendering from Unity to the Oculus HDM. Text messages were rendered only within the center of the user's view, while other indicators such as some of the system statistics were rendered via alternative cues such as sound and graphics elements. Along this line, we explored superimposed visualization as on-demand visuals which are attached to certain objects within the immersive environment. Such superimposed visuals are scaled relative to the user's eye (or camera location), allowing to simplify the user interface while still providing awareness of the simulation variables and status.

6.4.1 **Interaction Features**

Interacting with JackVR requires the user to wear an Oculus Rift HMD enabling immersive depiction of the 3D environment and its surroundings (Figure 6.5). Within the JackVR immersive environment the user is interacting with a rich set of simulation graphical representations including animated 3D ocean waves (with a simple buoyancy), sky and clouds (through a skybox), a set of floating ships over the sea surface, a jackup rig 3D model, and underwater effects (implemented using Unity3D, Figure 6.6). Furthermore, basic audio support has been integrated to further enhance the immersion of the experience.

In the actual landing process, the operator needs to observe the rig and its legs from different perspectives during the landing, and to be able to interact with the rig by moving its legs up and down, or by raising the rig's hull as needed. We mapped these task interactions to fit the design of VR simulation. We realized that the simplicity of the ray-casting interaction technique [23] (Figure 6.6) makes it a seamless and a suitable choice for such mapping.

We decided to enable interaction with the JackVR immersive environment using the ray-casting technique, as it fits the navigation and control around the rig. First, with regards to navigation, we wanted to support users with a first-person flying experience to be able to directly see the 3D rig

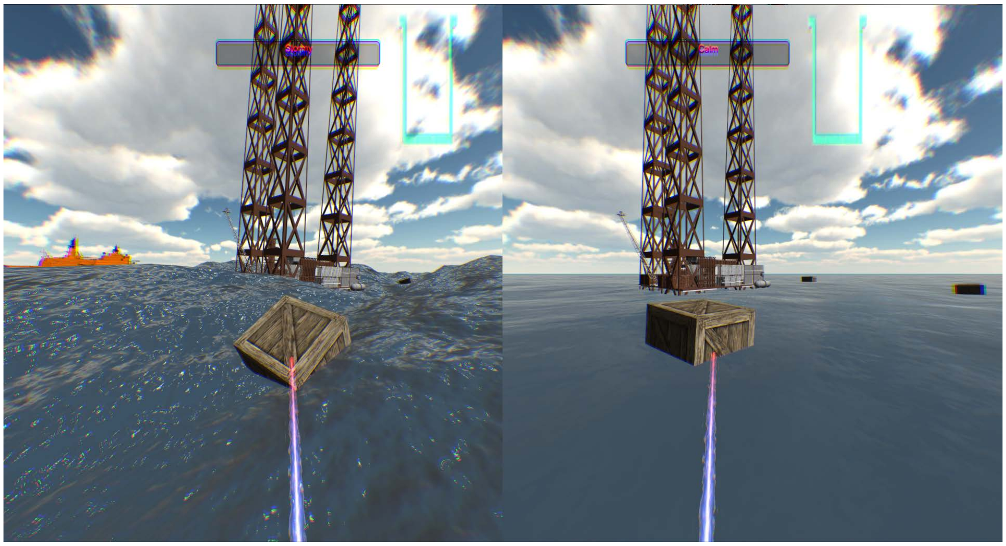


Figure 6.6: JackVR and the ray-casting interaction technique in two ocean conditions: high stormy waves (left), and calm waves (right)

from any point during the simulation. Second, to control the rig, it must be "selected" first, and the design of the ray supports that as follows: the ray is rendered as a virtual screen-inward laser pointer reflecting the user direction. When the ray intersects objects within the 3D world, it can cause specific visualizations to appear and can enable direct interaction with objects. For example, when the user is oriented towards the rig model, the ray will enable a specialized visual element attached to the rig which indicates its current status (Figure 6.7). The ray casting approach and the superimposed visualization provide details-on-demand, which prevents over-population of the user's view, and allows direct access to faraway objects.

JackVR uses a Xbox controller to support a gaming-like interaction within the simulated environment. The user can navigate the environment using both the left-analog stick and HMD movement. The controller's buttons are used to control the rig itself. For instance, the "X" and "B" buttons are used to control the rig's legs while the "A" and "Y" are dedicated to raising and lowering the rig's hull.

Sound is utilized as a second sensory element in addition to visual elements. Our initial implementation only supports sound-based feedback when the user is traveling within the virtual environment. For instance, the sound of air while moving above surface differs depending on the user's traveling speed, and moving under the sea level will result in ambient underwater sound effects. Sound can be used beyond the aforementioned effects, e.g., as auditory warnings that aim to notify the user of sever issues regarding the landing process, which we are exploring as future work.

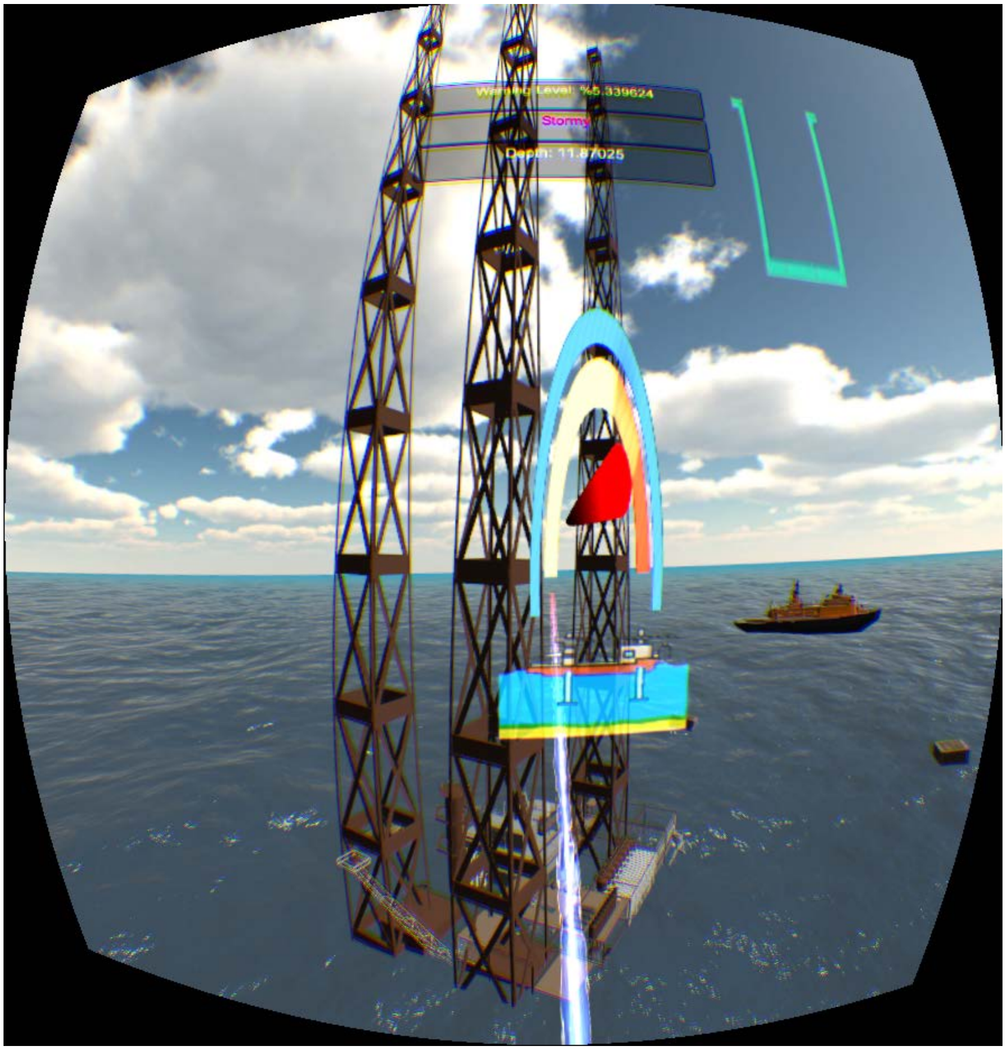


Figure 6.7: JackVR's "superhuman" mode is active

JackVR design is focusing the user's attention on the immersive experience. For example, when a landing problem is indicated it will not be reported numerically or as text, but rather via a visual notification cue such as a red overlay. The rendering of this visualization takes inspiration from games and is blended over the final rendering frame with a transparency that is relative to the current warning value (Figure 6.8). While JackVR can integrate the more typical notifications (e.g. textual-based messages, or 2D graphs), it enables with rich superimposed visualization that provides more direct seamless information superimposed on the main rendered simulation objects.

The JackVR visualization status varies based on the selected mode. When the normal-mode is active, the user interface relies on basic textual status indicators, while still allowing the user to fully control all simulation aspects. When the superhuman-mode is enabled, the user is empowered with a set of superimposed visualizations including visual bars, indicators and meters which are integrated within the immersive environment components. For instance, a visual meter (similar to cars speedometers) reflecting the current warning level would appear when facing the rig (Figures 6.8).

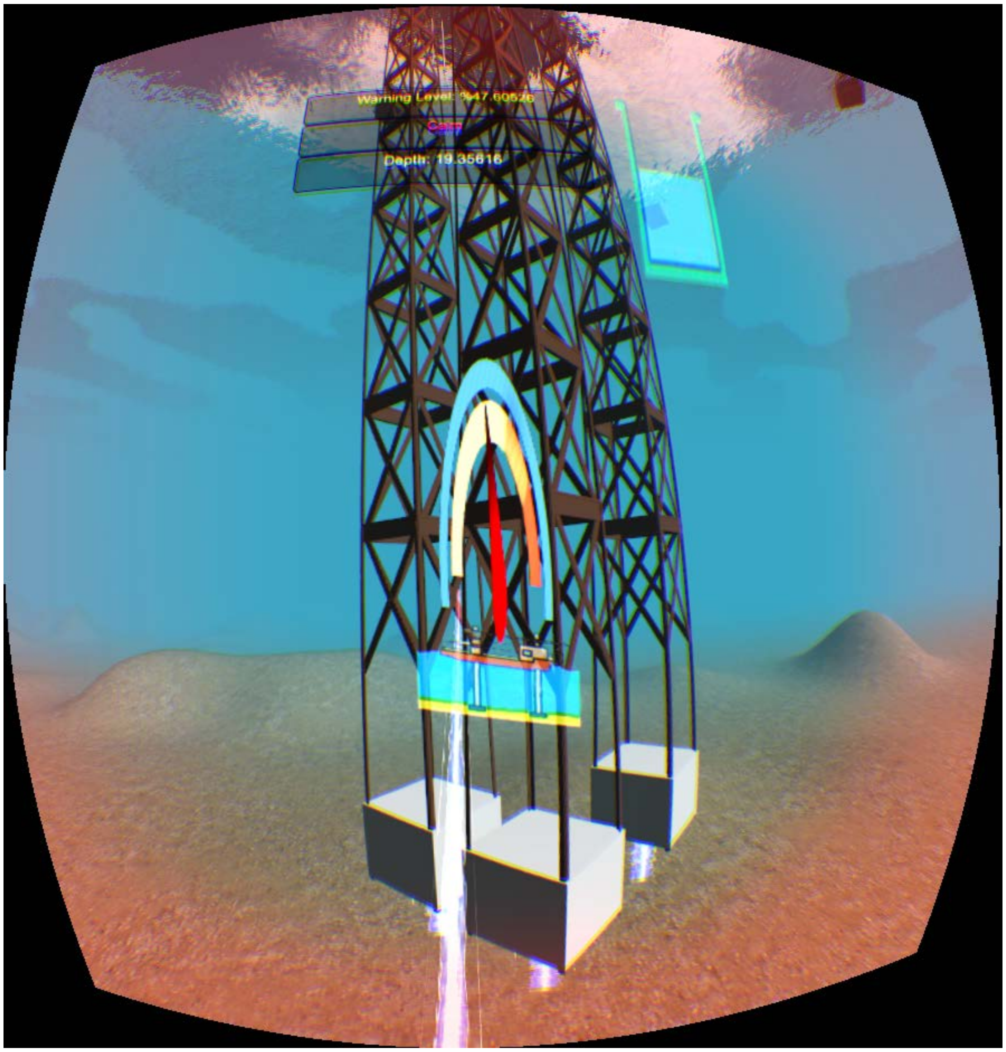


Figure 6.8: Warning level representation in superhuman mode

In the superhuman mode, various graphical interface elements have been implemented aiming to assist users and inform them of the simulation's status. For instance, the parameter representing the water level inside the rig is simulated through an icon reflecting two states of the water level inside the rig's tank (either empty or full). Similarly, the leg depth parameter is represented by a floating 3D indicator showing the current depth relative to total depth of seabed (Figure 6.8).

Upon completion of the training, a graphical notification of either success or failure is shown. The user can still navigate around the environment after finishing the training, but at this point cannot change or interact with any object within the virtual world. We enabled this post-task view in order to provide the user with an opportunity to reflect on the task performed and on the reasons for landing success or failure.

6.5 Discussion And Future Work

JackVR is still a proof-of-concept prototype, and while it was designed iteratively with domain experts, we still did not fully evaluate it as a practical training tool. Current preliminary feedback from a senior domain expert points to JackVR potential help to engineers who are learning the oil-rig landing process, its ability to provide a sense of difficulty and unexpected hazards, which might happen and cost companies millions of dollars.

An example of future work here would include running a formal user-study of JackVR to gather in-depth feedback from its potential users to refine the representation and better support the domain users expectations.

6.6 Conclusions

We presented JackVR, an experiential VR simulation aimed at training oil-and-gas practitioners in landing offshore oil rigs, focusing on the process of landing a jackup rig as a widely used off-shore drilling unit. JackVR incorporates features that simulate the landing process as well as the surrounding environment, including seabed topography and ocean waves. Users can change the simulation parameters, and practice a variety of scenarios. JackVR also supports a superhuman mode which superimposes 3D indicators with the immersive environment, and enables a ray casting interaction technique.

Chapter 7

RoboTeacher: A Humanoid Robot Instructor for Industrial Assembly Tasks

In this chapter, we propose the use of humanoid robots in teaching assembly tasks to workers. We argue that these technological instructors reflect a unique approach to mediating experiential learning in interactive contexts. We offer an assembly robotic instructor prototype based on a Baxter humanoid and the results of a study conducted with the prototype teaching the assembly of a simple gearbox. It is worth noting that parts of the work presented in this chapter has appeared in the following publications [187].

7.1 Introduction

In industrial working environments, especially in the assembly industry, it is critical for workers to learn how to carry out a new task and reproduce it within the context of an assembly line. Before workers can be employed in a production line, they have to become familiar with all the steps of the assembly process. For example, in the case of a gearbox manufactured in a production line, workers have to train in performing the complex assembly process several times in order to ensure a flaw- and frictionless assembly.

There is a widespread need for supporting methods that help workers learn new assembly skills. Currently, "overseers" - observers or mentors - instruct, guide and supervise workers during the learning process. However, many challenges arise when relying on overseers. Drawing on our combined experience, and collaboration with the assembly industry, we present two examples of challenges we hope to address: (1) there may be difficulties in serving individual learning needs of different workers; and, (2) there are a limited number of skilled overseers qualified to teach specific components of a complex assembly processes within the relevant context of the assembly process.

Our research aims to tackle these challenges by exploring new ways to design and improve the learning process using robots. Our goal is to understand how humanoid robots can teach new assembly tasks to a worker, freeing up scarce resources of available human overseers, while providing a quality learning experience, which includes learning the tasks required and experiencing the learning process in a positive way.

Following strict research ethics and safety guidelines, we developed an assembly teaching prototype using a Rethink Robotics Baxter humanoid as an assembly task instructor (For a detailed background about humanoids refer to Appendix A). We then conducted an evaluation study of our approach to verify if it is possible to train an inexperienced worker to successfully assemble a mechanical gearbox. Our goal was to explore how humans interact in this learning situation, and to measure user experience (UX), reflecting on acceptability, intimidation, and other factors related to collocated interactions with robots [10]. Out study also involved reporting on training by humans and how it may differ from robot-based instruction. The results of our study demonstrate that humanoid robots can become effective assembly line instructors, and have the potential to provide alternatives to visual-only learning systems such as print, video, or augmented reality. It is worth noting to highlight that my role in this project involved proposing and refining the design, guiding the system implementation, designing the evaluation study, and drafting the project report for publication. The role of my collaborator involved participating in the design and implementing the robotic interface, as well as running the evaluation study.

The contributions of this project are as follows:

- A novel design and implementation of an assembly humanoid-based teaching system;
- A study providing results that explore why and how humanoid robots can be instructors for industrial assembly tasks.

The remainder of the paper starts by highlighting the design rationale for our prototype. We then describe the technical system components, and detail the study conducted. We conclude by presenting our results, and discussing implications for future work.

7.2 Prototyping A Humanoid Teaching System

Our approach integrates a humanoid robot into a teaching system we call RoboTeacher, where the robot takes on the task of overseer or instructor teaching the industrial process of mechanical assembly. We argue that while assembly tasks might be automated completely by other robots, current assembly industrial processes are still dependent on humans that cannot to substituted by robots. Therefore, we focus on addressing the current lack of skilled experts to train "novice" new workers.

The robot trains workers in the assembly process by giving instructions for each step, providing relevant information for critical complex contexts, and offering assistance for potential errors. The teaching system is not limited by time, capacity or language constraints [249] as in the human, overseer approach. In other words, the proposed system allows any person regardless of linguistic differences to be trained by Baxter, whose instructions are encoded and can be localized as needed. These efficiencies lead us to believe our approach will reduce training costs, and enable inexperienced learners, as well as those requiring additional experience, or who face language barriers, to learn and work on an industrial production line.

7.2.1 Early Explorations

Beginning our research, we conducted pilot sessions to study how people teach and learn technical skills, how technology can support such learning, and how the Baxter humanoid robot, can support or take on the role of instructor.

We first identified basic elements of instructions that a human uses while teaching (Figure 7.1). These elements include expressive gesturing, specific pointing, speaking, and demonstrating with tools such as images and video. Our exploration simplified apprenticeship-based learning demonstrated that humanoid robots have the potential to substitute many basic elements involved in teaching a new mechanical assembly task.

Figure 7.1: Example of one of the pilot sessions.

A key design exploration during our pilot studies focused on understanding the capabilities of Baxter as a humanoid instructor. Baxter has: a rotating, face-like display, a camera, and movable arms with flexible joints (Figure 7.2). We explored variations of Baxter's speed of motion, range of movement, and the ability to display media. We found that Baxter is able to successfully perform complex gestural movements with its arms and grippers, but was not as fast as human motion when moving between task-specific locations. When playing multimedia, Baxter is capable of providing supplemental media (e.g., text, images and animation) that support the teaching of critical contextual aspects of assembly tasks. By implementing speech synthesis software, Baxter can also speak. This speech can operate in any language, accommodating learners not fluent in the original language of instruction.

Another design criterion requires generic system development supporting usability with any type of (humanoid) robot. Although our work involved Baxter, the software, and methodology, can be generalized for adaptation to other robots and approaches. This transferability is achieved because of a design architecture that abstracts robot actions into simple commands (e.g., move to

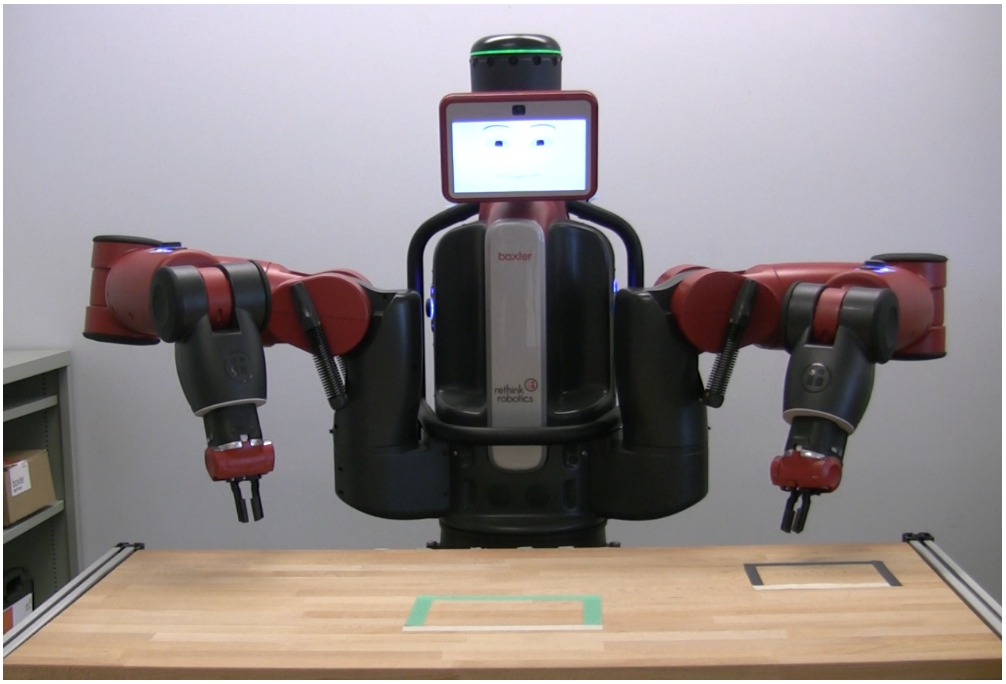


Figure 7.2: Baxter, our humanoid robot instructor.

a specific location, show a specific rotation gesture, etc.).

7.2.2 Techniques to Support Teaching

Many of existing learning systems use visual techniques to teach tasks. Examples include, the use of virtual, augmented, and mixed reality, and computerized simulation. While there are advantages to these approaches, such as low associated cost, portability, and ease of deployment, there are many disadvantages. Clearly, such visual-only techniques lack the physicality, spatiality, and personal aspects (e.g., facial expression and movement) a human instructor provides. These interaction cues are essential to provide effective teaching and learning. Further, occlusion of physical objects or interface elements often result when augmenting physical task components with in-situ visualization, thus hiding some task operations, or making them unclear, which hinder an efficient learning process.

7.2.3 Our Approach

We designed, developed, and evaluated, an assembly teaching system (ATS) utilizing the humanoid robot Baxter, which is capable of basic hand gestures, movement, as well as displaying media that simulates facial expression. While we acknowledge the importance of robotic gaze [71] we decided, mainly for experimental simplification, to support Baxter with basic head movements while displaying a simplified human-like face. By utilizing a humanoid robot, our proposed approach aims to provide a moderate solution between the low cost visual-only approaches, and the expensive option of making a human instructor available for all learning interactions.

The design of our prototype provides step-by-step instructions to train workers on the assembly of a simple gear box. This task includes 23 assembly steps. The humanoid robot explains each step in succession using hand gestures, visual diagrams, and speech. Our generic design, utilizing XML, supports any kind of stationary assembly process, and any kind of humanoid robot. In particular, mapping the structure of any assembly task through our XML format is achievable using the primitive learning steps we identified (e.g., robot movement, gestures, etc.). We added support to encode patterns for repeating task components, which simplifies the creation of assembly plans. Using XML for assembly tasks, our approach allows for the embedding of specialized tags to address user mistakes (e.g., branching to assist a trainee when he or she makes a mistake during the teaching process). This approach allows for future work, task flow, instructions, and potential errors that can be automatically generated by an artificial intelligence component, thereby simplifying the creation of project-specific XML content.

We conducted an evaluative study to verify whether it is possible to train an inexperienced person in a specific assembly task. In addition, we explored human interaction in the learning process with the robot. Our UX measures include reflection on acceptability, and other factors relating to interactions with robots [10].

Since our focus is on the UX, we designed our Baxter prototype to operate through a high-level Wizard-of-Oz approach [149] where, unknown to the trainee, a human operator or "Wizard" oversees the robot's actions. This manual operation mode simulates the output of an artificial intelligence algorithm, which could be implemented in future designs. While this approach was crucial to our study, it is important to note that our Baxter prototype already includes completely functional gesture, and media modules, for step-by-step assembly instructions. The Wizard controls only the instructional flow: e.g. selecting the next step for the robot to perform, or to repeat a step.

7.3 System Description

The following section describes the assembly teaching system prototype, used to evaluate whether, and how, humanoid robots can teach industrial assembly tasks.

In this work, we used Rethink Robotics' industrial humanoid robot Baxter. Baxter is dual-armed, and 1 meter tall providing seven degrees of freedom. Pedestal mounting enables stationary usage in a single, fixed location.

7.3.1 Architecture

As described in the previous section, the robot should impart instructions to the user, in a human style, using arm gestures, speech, and facial expressions. Thus, our design divides the prototype system into two discrete units; the robot acting as the presentation medium, and the Assembly Teaching System as a back-end application that assumes all information processing tasks (Figure 7.3).

Baxter can be operated using the Robot Operating System (ROS) open-source framework [73], which allows a simple application creation using the Python API provided. The framework allows the implementation of actions such as moving each of Baxter's joints to a specific position, controlling of grippers (hands), or setting the content to be displayed by the head (screen). These actions are published by ROS to the robot for execution.

Using ROS we developed an application that serves as an interface for the Assembly Teaching System. By making this interface available using socket connections, the Assembly Teaching Sys-

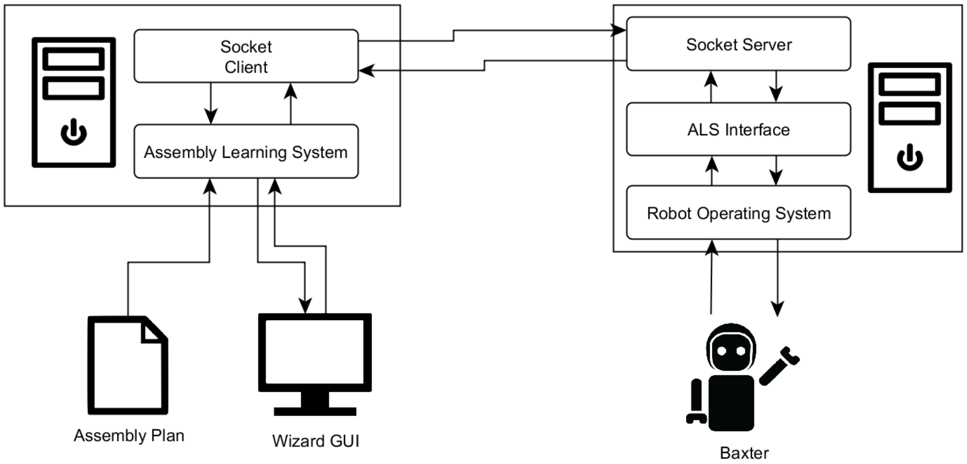


Figure 7.3: Structure of Assembly Teaching System Components.

tem is able to send actions in a predefined format to the interface, and thereby control the robot. This client-server architectural approach isolates the control unit of the robot from the operator application, which provides robot-instructions. This encapsulation makes the system generic, enabling it to operate with different kinds of robots without the need to revise the whole system whenever one of its components changes.

7.3.2 Task Representation

The Assembly Teaching System contains all information required for the assembly training. In lay terms, an assembly-training task needs to be simplified as a set of steps, which can be sent to the robot one-by-one for execution. Depending on the user's response to a given instruction (e.g., the user correctly performed the step, or made a mistake), the software decides which subsequent step appropriate. We implemented a flowchart utilizing state machine to represent the sequence of events for the assembly process of the gearbox object used in our prototype (Figure 7.4). Each state of this flowchart represents an instruction given to the user. The transition between states is determined by the outcome, or user action.

It took several iterations to identify and optimize the individual assembly steps for the gearbox object, as described in the pilot study below. Our final description involved 23 concrete assem-

Figure 7.4: Gearbox object (top) and its discrete parts (bottom).

bly steps, and 22 state transitions required to represent the necessary information for successful assembly (Figure 7.5).

A challenge for this type of state-representation is that the generated steps only cover the ideal flow of the process, and exclude potential user mistakes. After incorporating the most common, and predictable, mistakes a user might make during the process, and then matching them with an appropriate solution, the flowchart contained more than 100 steps, and 200 different transitions, which created the need for a more precise representation.

Analyzing the flowchart, we isolated several repetitive instructions. Our results indicated that for these types of instructions, predicted failures, and subsequent resolution steps were always the

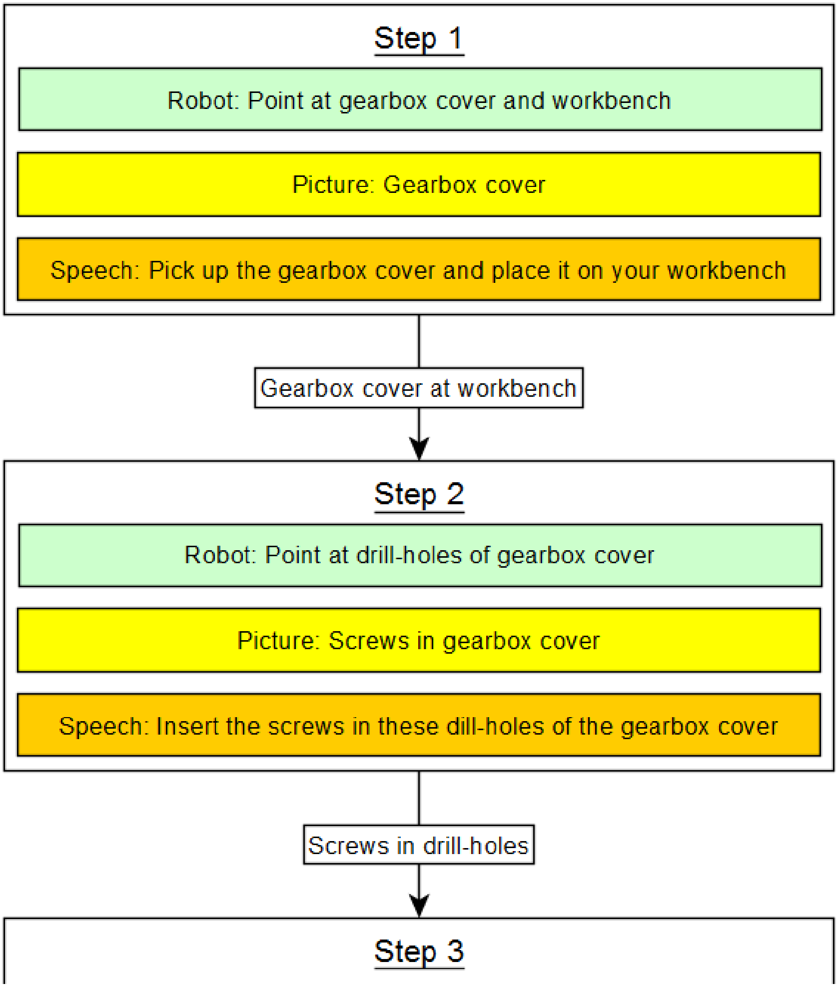


Figure 7.5: Example of a 3-step flow diagram without failures.

same. One example is the instruction, “Pick Object A and place it at Position B in Orientation C”. Predictable mistakes in this case include the user picking the wrong object, or placing it at the wrong position/orientation. These findings allowed us to introduce “patterns” to represent repeating procedures in an efficient manner. As a result, our methodology provides a significant simplification while sequencing the assembly process.

7.3.3 Implementation Details

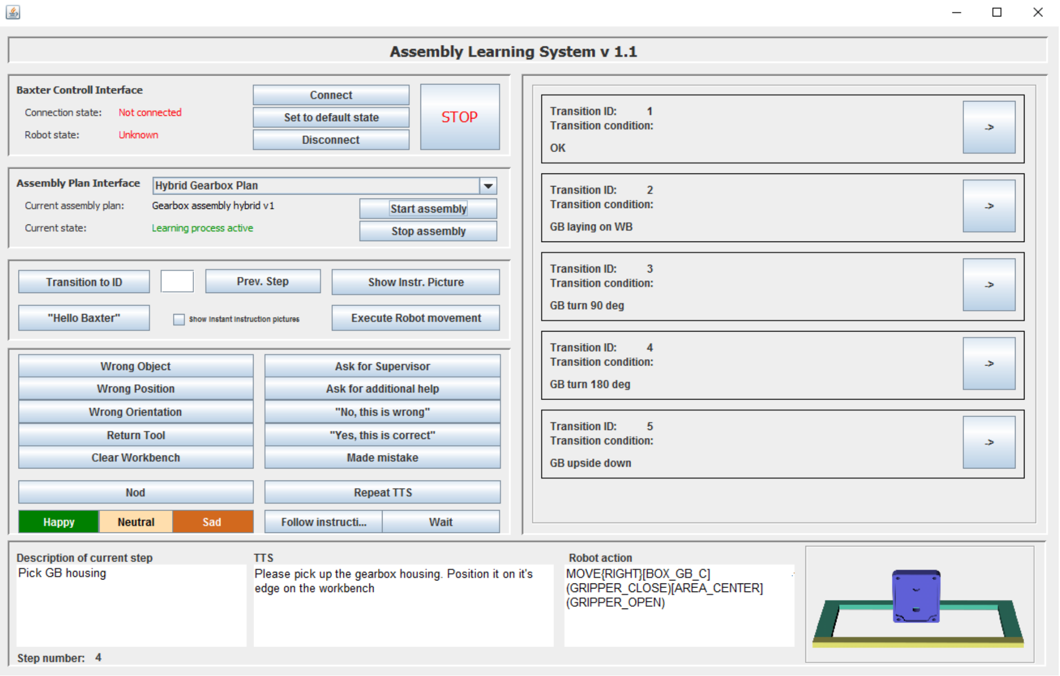
We implemented a Java-based, state-machine component that maps the XML structure mentioned earlier. This method streamlines the move between the instructions’ steps based on transitioning conditions. By representing steps in a data packet structure, networked communication offers an efficient means to engage the robot interface.

To provide audible information, in addition to the visual movements, we used the SemVox Ltd. ODP S3 Speech Dialogue Platform [83]. This platform enables not only speech synthesis of the information defined in the assembly instruction files, but also the ability to talk and control the system by voice input. By placing speakers and microphone near the robot, the user gets the impression that the robot is talking and understanding during the interaction.

To support evaluating the system using the “Wizard of Oz” approach, we developed a graphical user interface (GUI) that allows the experimenter to control the robot indirectly through the Assembly Teaching System. As shown in Figure 7.6, the GUI provides the functionality to load and navigate through an assembly plan.

As soon as the experimenter starts an assembly teaching process using the Wizard GUI, the robot executes the instructions for the first step. The operator can then choose how to proceed. If the user follows the instructions given by Baxter, the operator can choose the function “OK” and the system proceeds to the next step. If the user makes a mistake, or needs guidance, the operator can choose the appropriate function from the list of mistake protocols. This action initiates a step providing a solution for the problem along with detailed, corrective information.

It is difficult to design for all user mistakes, so the Wizard GUI contains several functions



Connection state: Not connected
Robot state: Unknown

Hybrid Gearbox Plan
Current assembly plan: Gearbox assembly hybrid v1
Current state: Learning process active

☐ Show instant instruction pictures

Transition ID: 1
Transition condition:
OK

Transition ID: 2
Transition condition:
GB laying on WB

Transition ID: 3
Transition condition:
GB turn 90 deg

Transition ID: 4
Transition condition:
GB turn 180 deg

Transition ID: 5
Transition condition:
GB upside down

Description of current step
Pick GB housing

TTS
Please pick up the gearbox housing. Position it on it's edge on the workbench

Robot action
```
MOVE{RIGHT}[BOX_GB_C]
(GRIPPER_CLOSE)[AREA_CENTER]
(GRIPPER_OPEN)
```

Step number: 4

Figure 7.6: Main interface of the Assembly Teaching System.

to provide general help given as user feedback. The operator can choose from of a list of 12 sentences to be spoken aloud by the system. Examples of spoken feedback include “This is the wrong position for this object”, “Please return the tool to the toolbox”, and “Yes, this is correct; well done”.

For complex assembly steps, or situations in which a user has difficulty following an instruction, a picture can be displayed on Baxter’s screen, clarifying the instruction steps. Currently, Baxter only gestures to the correct location (that was captured earlier) or indicates the action to be carried out (following the currently being executed layout and guided by the human assistance). This behavior may be extended allowing Baxter to physically grasp or manipulate objects during the training to demonstrate complex assembly steps where the trainee has failed after multiple attempts. It is worth noting that this approach can still be limited in supporting particular assembly steps that require flexibility beyond what can be provided by a robot (e.g., complex rotation or fast interaction). Our research shows that the robot as physical entity best supports learning, and thus refrain from abstracting the learning process by merely loading images on Baxter’s screen. Instead,

Figure 7.7: Examples of Baxter's facial expressions .

further humanizing the robot presenting emotional, facial responses is of benefit. The robot can express mood by presenting facial expressions, which extend the anthropomorphic capabilities of the robot.

By default, Baxter's screen shows a neutral facial expression. If needed, the operator can trigger a "happy" or "sad" expression, to acknowledge that the user carried out an action correctly, or to indicate when something was unsuccessful (Figure 7.7).

7.3.4 The Training Environment

After implementing the system, we planned the working area for the user and robot. Our aim was to create a face-to-face learning situation. The workspace was a workbench, containing separated parts of the assembly objects, a toolbox, and several process-specific areas (Figure 7.8).

We used a one meter high table, allowing the user to stand. The standing position is designed to make the user feel more comfortable while working with the approximately 2 meter high robot on the other side of the table. A user unfamiliar with humanoid robots might feel uncomfortable sitting at a height well below the robot. The user's position opposite Baxter, allows them to take a step back at any time taking them out of reach. This positioning, along with the table as both work space, and physical barrier, is intended to make the user feel physically safe with the robot.

On the workbench, several boxes for the raw parts and tools can be located. The workbench space is subdivided into different regions in order to prevent a collision of the robot and objects on the table, and to simplify the planning of movements. Masking tape marks specific areas on the workbench. The center marked area is intended to serve as the space where assembly is carried out. The second area can be used, to temporarily store a tool, or partially assembled object needed

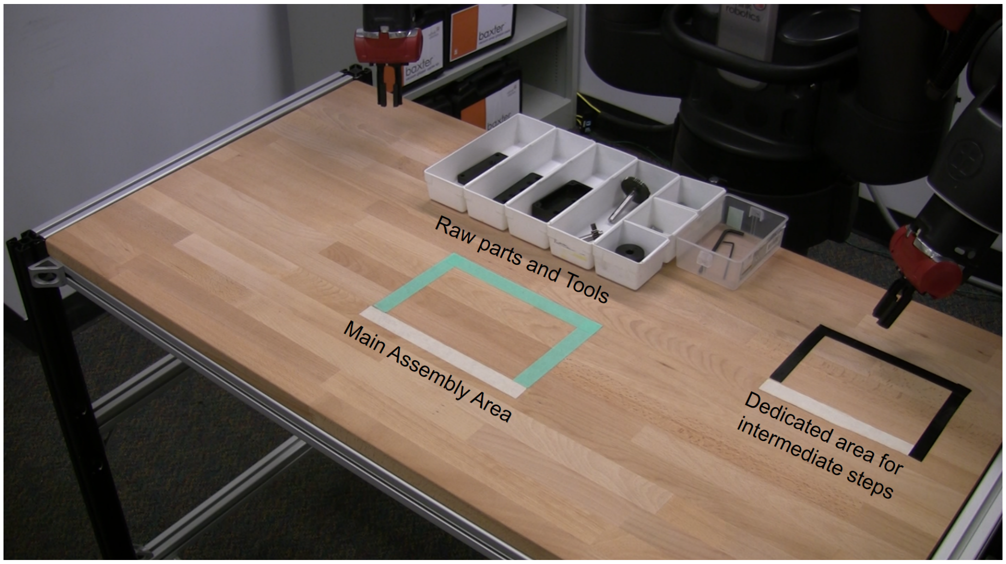


Figure 7.8: Spatial configuration of workbench used in our setup.

later.

To define the robot arm-movements for teaching each of the assembly steps on the workbench, we developed a motion-planning tool using Baxter's "Zero-G" mode. In this mode, operators manually move Baxter's limbs to specific positions capturing coordinates. The captured coordinates represent key points that can be stored in the Assembly Plan, for later use in the automatic calculation of the complete movement trajectory.

7.4 Evaluation

We conducted an exploratory study to answer the question of whether and how a robot can take on the tasks of an overseer when teaching industrial assembly tasks. As part of this work, we analyzed how efficiently a robot can impart knowledge when operating an instructor. As mentioned above, our study went through, and was approved by, a rigorous ethics process at the host university . In addition to the required elements, security measures were added when the robot physically led participants including, (1) active observation by the researcher throughout the process allowing intervention as needed; and, (2) a fail-stop button positioned at the side of the participant allowing him or her to immediately shut down the robot. As part of the research ethics committee's process, a protocol for introducing, and reviewing these procedures, and safety measures, was presented in detail with each participant. One of the areas of interest for our team was the level of comfort experience by human operators interacting with the Robot instructor. As such, we watched closely for moments of even the slightest discomfort to maintain the integrity of our work, and to refine our process for broad-based adoption. Participants in the study were interested in the work because of the human robot interaction, but we encouraged an awareness of discomfort to explore any potential challenges for future implementations of the approach. This focused, and labor-intensive approach to research is one of the key reasons that our test group was kept to 15 participants. At the same time, the intense focus of this approach is one that provides clear outcomes for the research team to analyze, synthesize, and further test.

7.4.1 Participants

We recruited 15 participants (10 M / 5 F) from a local university for our study. In the recruitment process, we considered participants of varying age and gender and did not require prior knowledge of industrial assembly tasks. All participants who volunteered were included in the study, and the demographic composition of participants was a direct result of this open recruitment process. Out of the 15 participants, two were familiar with complex assembly tasks, though not with the gearbox object used in this study.

We also recruited 5 control participants (3 M / 2 F) from a local university who participated in the our study trained by the experimenter and not the humanoid robot Baxter. On one hand, we acknowledge that training by a human instructor would be more effective than receiving instruction from a robot, but we wanted to include some objective results to support this condition. On the other hand, we still argue that training by huamnoid robots provide unique benefits. For example, the robot can train in different languages, and does not get tired, and can be more available than skilled human instructors.

7.4.2 Task & Context

For this study, we used a small gearbox as the assembly object (Figure 7.4). The gearbox contains 16 parts that have to be put together in specific position and order. We identified the steps needed for the assembly and specified an order in which the steps must be performed. Our approach, requiring a strict order of actions, simulated a realistic scenario in which workers must strictly follow a specified method of assembly with no room for improvised action, or trial-and-error approaches.

The gearbox used for our study is simple. An experienced worker should be able to assemble it in less than 5 minutes. While simple, the model provides a valid assembly task, and includes the opportunity to make several assembly mistakes during the process.

The experimenter controlled the assembly teaching system through two computers while sitting three meters away from the workbench and table. Since the experimenter assumed the role of the "Wizard" of the system, he or she had to be aware of what participants were doing at all times. To simplify the Wizard task, we streamed live video of the workbench to the second computer used by the experimenter using Baxter's head-monitor camera.

7.4.3 Structure

Each session lasted around 45 minutes, starting by welcoming the participants and giving them an overview of the project, and the robot. Participants were first trained (multiple times) in the assembly with the robot as the instructor. Afterwards, they were asked to carry out the assembly process on their own to assess the success of the training. The self-assembly was the last practical part of each session. Participants were asked to carry out the assembly on their own without help. In addition, they were specifically told that self-exploration of the task was prohibited, and that they must carry out the steps in the order Baxter instructed.

The 5 participants of the control group followed a similar study protocol, wherein each session included training of the same assembly task twice, with the experimenter acting as the overseer instead of the robot. The experimenter gave the instructions in the same order as the humanoid robot. After the training, the control group participants were also asked to carry out the assembly on their own.

We implemented post-session questionnaires to obtain insight into the personal experience of participants. We used the “Godspeed” Questionnaire [10], which is an established model for rating human experience with robots. 23 of the 24 questions from the full Godspeed questionnaire were used, with question 9 “artificial” removed because it was confusing to participants (based on our pilot sessions). We then asked participants to complete a questionnaire we designed to rate specific parameters of the robot in the study. We included questions asking if they liked Baxter and our system, if they would rather train with a human, if Baxter’s movements were helpful for understanding the task, and if they wanted to talk to Baxter.

7.4.4 Study Description

We conducted a pilot prior to our evaluation to refine our study protocol, and assess whether the system, and study design would fulfil the stated purpose of the study.

Pilot Explorations

During the pilot study, we experimented with two different assembly plans. The first one was a highly detailed assembly plan, dividing the assembly instruction into 24 discrete steps (without error handling). Each instruction from the robot included great detail. We also used pictures to clarify complex instruction steps, displaying them on Baxter’s screen, providing hints to the user. The second assembly plan simplified the first, combining each group of logically associated steps into a single step. This streamlined plan required only 12 steps, enabling faster assembly, if, and when, the user performed the steps without errors.

In the pilot study, three participants were allowed to train in the gearbox assembly process up to three times with Baxter’s help before being asked to assemble the object without assistance. At the beginning, the detailed plan was followed by a short questionnaire asking if further training was needed, and if the comprehensive (detailed) plan should be used. Depending on the answers, the participant would train for a second, or even a third time, or he or she would be directed to self-assemble the gearbox object.

Final Study Design

Following our pilot explorations, we conducted our study with the 15 participants we recruited. Our final study design utilized what we learned from the pilot sessions. In this section, we provide a detailed description of how we conducted the formal study.

Our pilot created disparities between participants who selected different levels of exposure to Baxter's training by allowing them to decide to opt out of the second or third training run. To achieve greater consistency, we decided not to vary the procedure between participants. All participants were asked to perform the assembly three times with the robot. This modified structure was used when conducting the full study.

The feedback from the pilot indicated that the steps of the first assembly plan were too detailed, and consequently too time-consuming. Using this feedback for the full study, Baxter offered the simplified assembly plan as a default, only reverting to the detailed plan if needed. This procedure provided adaptive capacity in the training process to address the learning speeds of individual participants.

Initially, we noticed that some participants focused on pictures that accompany the assembly instructions, and did not pay enough attention to Baxter's movement and speech. Consequently, they made several mistakes since they were missing relevant information, which could not be derived from the pictures. Therefore, we decided to limit the use of pictures during the training, and only provide them as needed. If the user got stuck on a particular step, the experimenter could manually trigger the GUI to display a picture to help the participant complete the step.

We wanted to ensure participants waited until the robot finished the explanation of a step, before they attempted to carry it out on their own. This approach supports a more complete learning experience; and connects to previous studies (e.g. [181]) that explored how light can be an effective indicator for turn taking. We implemented a feature for Baxter that turned signal lights on while something was being explained. When the light turned off, the user would understand the robot has finished the instruction, and the user should now carry out the step.

7.5 Results and Discussion

The goal of our study is to assess the practicality of Baxter, as a humanoid robot, in teaching technical assembly skills. As mentioned earlier, our study involved participants who have trained with the robot using three training sessions.

The results revealed interesting insights into the effectiveness of our approach to supporting the learning of assembly tasks without a human overseer. Tellingly, every participant was able to learn the assembly task from the robot, and then self-assemble the gearbox object in a timely manner.

7.5.1 Baxter Training Results

Participants trained with Baxter for three sessions prior to conducting the self-assembly. As expected, our results show that participants' learning improved after each training session. As detailed in Figure 7.9, after each subsequent session, participants needed fewer steps to complete the assembly, made fewer mistakes, and required less help from the robot. We argue that it is the presence of the robot, and not the repetition of the task, that provides the most effective and efficient learning experience. This outcome arises from our process, which asks participants to refrain from self-training or memorizing the assembly steps, and to only focus on robot-provided instructions.

The combined training and assembly time of each participant, is a major factor of user performance. As shown in Figure 7.10, almost all participants required less time for each subsequent session with Baxter. This efficiency also extended to the self-assembly of the gearbox object.

During self-assembly, all participants managed to complete the task without mistakes, and in a reasonable time (average = 4 minutes). All participants except two followed the training steps taught by Baxter, indicating that Baxter was effective in teaching participants the assembly tasks.

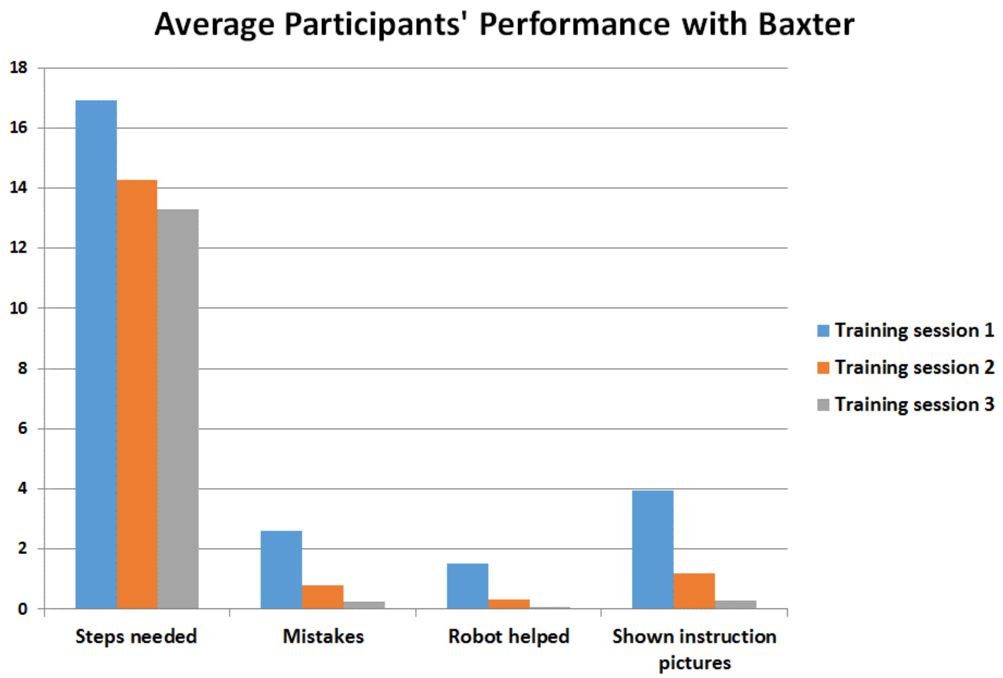


Figure 7.9: Average participants' performance with Baxter.

Questionnaire Results

The questionnaire responses also support our claim that Baxter is an effective and efficient instructor of the assembly tasks. All but two participants also stated they liked Baxter, and the teaching system. Eleven of the participants said they liked Baxter's feedback such as moving arms to guide them. As one expressed, "I think I could remember how to position the objects thanks to Baxter's arm movements". Interestingly, those who said they liked the robot suggested Baxter would be helpful training people with disabilities, or those who lack language skills required to work in industry.

Godspeed Results

The results of the Godspeed Questionnaire [10] revealed that most participants viewed Baxter as having human-like aspects, and thought that Baxter was conscious of their presence. This finding is also supported by our questionnaire responses highlighting that 12 participants were comfortable with the robot and Baxter's movement, with three participants claiming to be less comfortable, but only at the beginning of the interaction. As one participant expressed, "When my arm hits the

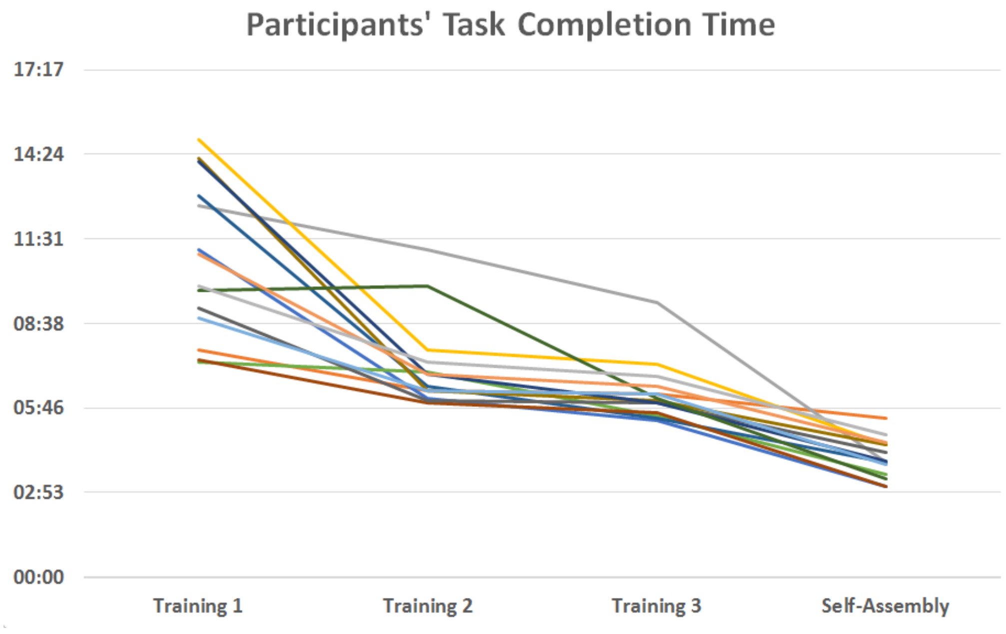


Figure 7.10: Participants' task completion time.

robot's arm, I was at first a little bit scared. But then I realized that nothing can happen to me and I started feeling comfortable". Supporting the anthropomorphic power of Baxter is the uniform declaration of a desire to speak with the robot. One participant made this clear by stating, "As I got stuck at a step, I wanted to ask the robot what to do. It would be nice if I could talk with him [or her]".

A well-trained, knowledgeable, and empathic human instructor can adapt to learners' abilities, and understand and respond to social cues as part of an optimal learning experience. Currently, this is done through the Wizard-of-Oz approach, and future implementations can enable full automation of such features. Our humanoid robot, however, provides elements not available in human instructors. Consider the need for instructors to train immigrant workers who speak different languages. A humanoid robot can easily operate as a multilingual instructor by offering translated versions of instruction materials. This option is particularly promising for teaching discrete procedures and tasks. Additionally, when working in such a multilingual, multicultural teaching environment, the disparity in social cues between the different learners, reduces the need for social cue expertise carried by the ideal human instructor described. Also, the usage of humanoid robots adds the

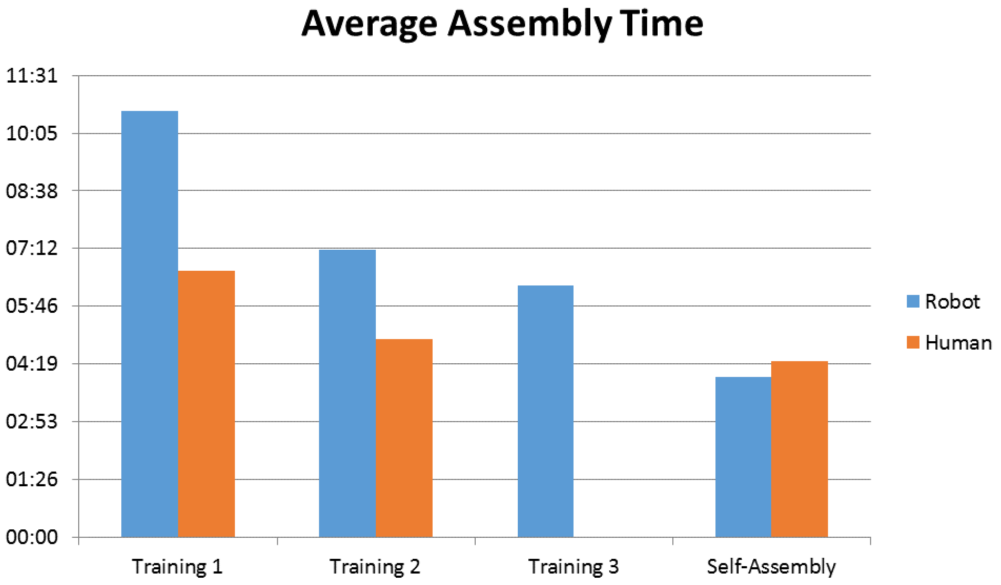


Figure 7.11: Average assembly time for all participants with Baxter and the human overseer.

potential to overcome the embarrassment felt by some trainees when failing repeatedly in a sophisticated task in front of a human teacher. Some participants expressed feedback supporting these assertions saying, "[I think that] using, a robot for simple assembly tasks is more efficient than a human teacher", and "I guess a human could detect any mistakes better than a robot. But involving a robot as overseer has many other advantages".

7.5.2 Training with a Human Overseer

Five participants completed the study with the experimenter as the human overseer. In general, all participants managed to complete the training and self-assemble the object with no mistakes.

While it is clear that a well-trained, knowledgeable and empathic human instructor will be a move effective teacher than Baxter in terms of adapting more easily to the learners' abilities and as possessing rich social cues that are essential for the optimal learning experience. We argue, however, that a humanoid robot can be an effective instructor who possess some of the social cues, and who can be superior even to humans in certain situations. For instance, it may be challenging to find an instructor to train immigrant workers who speak different languages, but a humanoid robot can easily be that instructor, just by uploading a translated version of the instruction material, especially for basic tasks. Some participants expressed similar saying that “[I think that] using robot for simple assembly tasks is much more efficient than a human teacher”, and “I guess a human could detect any mistakes better than a robot. But involving a robot as overseer has many other advantages”. Overall, every participant was able to learn the assembly task, and even though the training with the human seemed faster (Figure 7.11), the training with the humanoid robot leads to the same results concerning the learning outcome. In essence, the study results confirm our hypothesis that training with Baxter is reasonably effective to support quality learning experience.

7.5.3 Implications for Design

Here, we present the main insights gained from our study to support inform the important considerations for designing future humanoid-based teaching systems. First, it is important to optimize the design of arm movements so movement is parallels the speed of humans. Some participants complained that Baxter’s movement was slower than expected. Second, integrating machine-learning techniques into the design of future humanoids might improve the learning experience. This dynamic capacity would allow the robot instructor to respond to some of our participants’ expectation that Baxter be able to adapt to their skill level. To address this desire and realize learning and outcome efficiencies, the system implementation should include smart decisions, and adjust the level of instruction relative to each learner. Third, it may be useful to use mixed reality in conjunction with humanoid robots to create a richer learning experience when demonstrating challenging instructions, rather than using robot face screens to display simple images.

7.6 Conclusions and Future Work

We presented a novel approach for teaching technical assembly tasks utilizing a humanoid robot as instructor. We implemented an assembly-teaching prototype utilizing the humanoid robot Baxter with a flexible approach to teaching assembly tasks. We also conducted a study assessing the effectiveness of our approach, which provided feedback supporting our claim that humanoid robots are effective and engaging instructors of technical assembly tasks.

We envision various directions for extending our work. An experiment integrating our approach into an actual industrial setting would provide valuable data. A comparative study of our humanoid-based teaching system, and assembly learning systems based on visual-only techniques such as augmented reality would support the refinement of interaction, and identify contextual appropriateness for the use our approach. Within our current model, the use of the "Wizard of Oz" component assumed some of the higher level technical responsibility. Future development could take on more of the process, requiring less supervision at each step, eventually replacing the wizard, rendering our system fully autonomous.

Chapter 8

Discussion

Our research involved reviewing learning theories and prototyping immersive environments with the goal of mediating experiential learning. In this chapter, we begin by emphasizing the discussion of learning aids through our prototypes presented in previous chapters. We then reflect on guidelines for designing future immersive learning environments with educational aids. Finally, we present temporospatial elements involving many of our learning aids as a novel approach to enrich interactive immersive environments.

8.1 Practical Explorations of Immersive Learning Environments

In this section, we identify and discuss key themes for mediating experiential learning in immersive environments. Our discussion of those themes builds on the results of the prototypes presented in Chapters 4, 5, 6 and 7.

8.1.1 Surgical simulations benefit from usability and educational aids

In our first surgical simulation project (see Chapter 4), we focused on exploring how specific educational aids may benefit system usability and support the learning of novice users. We used the context of back surgery where medical experts can learn about and practice a common surgical task within an immersive experiential simulation environment.

At the beginning, we identified two major challenges facing our medical expert collaborators and limiting their adoption of existing simulators: complex interaction and lack of effective feedback. We hypothesized that such challenges are often related to poor usability and lack of effective learning aids. Accordingly, we argue that it would be beneficial for designers of such immersive simulation environments to consider usability guidelines in their designs. We also encourage such designers to consider and integrate relevant educational aids including guidance features, contextual visualization, and post-simulation performance measures. Ideally, we suggest that educational features should be incorporated from the inception of the model rather than as an afterthought to maximize the chance of enhancing the immersive simulation quality and the overall learning experience. This insight is in line with the feedback we received from evaluating our simulation prototype with medical surgeons and design experts.

The multidisciplinary nature of this research was a challenging factor for us throughout the whole project. We acknowledge that the difficulties we faced are common in the design of any multidisciplinary simulation systems. Based on our experience, we argue that it is crucial to build a common language of communication to ensure a successful research collaboration with the medical experts. This would mean using simplified jargons and limiting the use of technical terms during the discussion of experts' needs and expectations. It was also helpful for us to work closely with the expert collaborators, either by sharing the same physical space with them at the hospital, or through regular meetings at our lab. We engaged in learning and practicing some of the existing simulation systems used by the medical experts. We examined these systems hands-on, not only from the technical perspective, but also from the eyes of the medical users. Such involvement in their tools, enabled us to better understand their needs and expectations. As a result, we encourage designers of future multidisciplinary systems to follow a similar approach, involving target users (or learners) in the design process, and trying every communication possible to ensure a successful collaboration.

8.1.2 Interaction history enables repetitive learning

In Chapter 5, we described an immersive surgical simulation prototype augmented with novel interaction history features. Our goal was to deeply study a specific temporospatial learning aid and how users would benefit from such an innovative reflective capability. Participants who were involved in our prototype evaluation reacted positively to the implemented interaction history features, and mentioned various reasons for their feedback. They highlighted that the ability to see and interact with oneself past actions enables reflection and repetitive learning.

Many consider the linear undo/redo model to be effective for satisfying interaction-history design needs. We argue that the proposed non-linear history representation extends the simple undo/redo model in various ways. For example, the non-linear visualization may act as a unique aid, allowing learners to deeply reflect on their decisions and explore alternative interactions. Also, we consider the history visualization to be an effective tool for supporting repetitive practice, planning, and learning from mistakes within immersive experiential environments. Accordingly, we encourage designers to carefully encode the nonlinear history visualization in their learning systems. They also should aim to simplify the complexity of how users may interact with such a nonlinear visualization.

8.1.3 Gamifying simulation features enhances the learning experience

Games are a popular source of inspiration when it comes to improving learning as they better captiviate the user's attention and engagement. In immersive environments, we argue that gamifying some of the system features has the potential to facilitate learning in such environemts. In this regard, we reflect on our effort to gamify an immersive simulation of a common oil-and-gas task.

In Chapter 6, we prototyped an immersive environment for the experts to train landing oil rigs in a dynamic context. Users in our simulation can fly around the oil rig, receive gamified visual feedback reflecting their progress on the landing process, and superimposed visualization at objects of interest. The aforementioned explored ideas were inspired from games to enable quality learning and enrich the overall training experience. The results of our preliminary evaluation support how our immersive simulation has the potential to enable innovative learning and training of this practical task.

Our exploration is in line with existing research concerning gamified education (Refer to section 2.5 for more information). Although our implementation reflected a proof of concept, we aim to further consider unique gamification elements, including the integration of multisensory features such as sound and haptics toward achieving an authentic experience that better engage users and augment their learning.

8.1.4 Humanoid robots as teachers

In typical educational contexts, a human instructor or teacher is the source of knowledge and the one who possess the skills to educate others. We envisioned an alternative unique learning aid where humanoids can assume the role of teachers and become instructors. We explored this idea in detail in Chapter 7.

Our findings revealed interesting insights into the effectiveness of our approach to supporting the learning of assembly tasks without a human overseer. Tellingly, every participant was able to learn the assembly task from the robot, and then self-assemble the gearbox object without mistakes in a timely manner. Indeed, this result extends the initial training with the humanoid robot where all participants required less time for each subsequent session.

A well-trained, knowledgeable, and empathic human instructor can adapt to learners' abilities, and understand and respond to social cues as part of an optimal learning experience. We were surprised to know that our participant users viewed the humanoid robot as having human-like aspects and thought that it was conscious of their presence. This may indicate that the humanoid robot also offers adaptation to learners' needs and skills and can engage in some social cues.

Finally, we argue that such humanoid instructors have the potential to train people with disabilities or those who lack language skills required to work in industry. For instance, with the lack of human instructors to train immigrant workers who speak different languages, a humanoid robot can easily operate as a multilingual instructor by offering translated versions of instruction materials. This option is particularly promising for teaching discrete procedures and tasks. Additionally, when working in such a multilingual, multicultural teaching environment, the disparity in social cues between different learners reduces the need for social cue expertise carried by the ideal human instructor.

8.2 Guidelines for Designing with Learning Aids

In this section, we attempt to generalize our discussion insights, and propose the following learning aids as design guidelines that we anticipate would support future efforts of immersive learning environments.

8.2.1 Simplify interactivity

Designers of immersive learning environments should aim for simplicity and usability in their design of interfaces and interaction capabilities [171]. While this common usability suggestion is not new, it is still more valid for learning to ensure lower cognitive load especially for novice users. We argue that designers can always facilitate user's interaction by experimenting with different devices, changing task representations, interaction modalities, and by re-examining how users perform their tasks.

8.2.2 Explore effective content representation

Following existing information visualization theory and practice, we agree that it can be important to carefully represent the learning material in order to lower learners' cognitive load. In addition, it can be valuable to support different resolutions of the learning content and adapt a specific one to the learner's prior knowledge and progress with time.

The fields of information visualization and interface design have evolved with concrete recommendations that we also call for when designing representations of immersive learning experiences. For instance, a simple approach is to initially show an overview of the content, then enable zoom & filter, and finally present details on demand, as inscribed in the information visualization mantra by Shneiderman [211].

8.2.3 Appropriate Tool Fidelity

Building a learning system may involve integration of custom tools and devices that may be expensive or hard to get. One way to simplify this issue is through simulation, especially with careful consideration of fidelity.

In this new recommendation, we encourage designers to look for innovative ways to utilize affordable low-cost gadgets when building learning systems whenever possible. This is particularly important when learners would use the system in their own homes. For instance, when building an immersive simulation environment that involves haptics, designers should explore different types of haptic devices and select an affordable one that provides reasonable fidelity. Ideally, the implemented software should be built supporting a range of devices and automatically adapt the features of the learning experience based on the available user's device.

8.2.4 Provide feedback and performance measures

In general, providing minimal feedback during user interaction may not be sufficient. When designing immersive simulations, we argue for the importance of providing detailed performance measures and assessment reporting throughout the whole simulation process and especially at the end of it. Utilizing this new guidelines can particularly be valuable for learning purposes, allowing users to deeply reflect and learn from their own mistakes.

Designers should carefully design user's feedback. This is particularly important within complex systems where users are expecting meaningful feedback beyond a simple numeric score. Users appreciate and would often benefit from immediate and purposeful feedback that not only reflects on their progress, but also highlights what was successful and what went wrong. This could ultimately help users identify optimization opportunities and aspects for improvement.

8.2.5 Empower learners' memory and promote deliberate practice

A novel approach inspired from the theories of learning is to empower learners' memory and promote deliberate repetitive practice. Users need to be aware of their interaction history to reflect and better learn from their own mistakes.

The benefit of the experiential learning cycle [123] can be emphasized with deliberate practice that involves goal-directed learning, purposeful repetition, and immediate feedback. In this regard, simulators that enable deliberate practice of specific tasks with built-in expert guidance may provide a more comprehensive learning experience beyond just the technical skill development. Such simulators also have the potential to augment future hands-on learning within actual situated contexts [93]. These experiences, in turn, lead to building of explicit and implicit memories depending on the specific design of the simulators.

In general, computer simulators may be superior in promoting explicit memory especially if they were carefully designed. A potential design improvement here is incorporating active directed guidance and feedback before, during, and after the simulated task to provide a more dynamic learning. For example, it may be beneficial to provide clear instructions prior to starting the simulated procedure as well as on-demand guidance during the interaction. In addition, it could be valuable to provide information on enhancing performance with clear steps of how to correct procedural mistakes that were made.

8.2.6 Support individualized independent adaptive learning

This novel aid, inspired by the theoritical concept of scafolding [31], calls for engaging immersive experiences with a smooth learning curve where learners are able to learn in an individualized independent manner. The design of simulators need to be user-friendly allowing novice trainees to quickly and easily operate the simulator without the constant need of technical support.

One of the key goals of simulators should be to enable standardized learning of basic principles and individualized learning opportunities. For instance, current simulators should employ generic models as the base of their simulation. This can be beneficial for novice learners as it enables focus towards foundational concepts and skills in a standardized manner. As learners advance in their knowledge and skills, simulators designed for individualized learning can adapt to the different learning curves of individual trainees.

8.2.7 Contextualize learning with authentic environments

In general, authentic learning environments allow learners to be situated within the educational context. Such environments also replicate important contextual aspects toward full immersion of users and have the potential to mediate experiential learning in these immersive contexts. The success of such systems in duplicating actual tasks and user scenarios would also contribute to improving the transfer of learning.

Our suggestion through this new guideline for designers of immersive authentic environments it to aim at supporting motivational elements and maximizing users' presence and engagment. In part, designers should aspire to including as much contextual details as possible. For instance, when medical learners need to practice a specific simulated procedure, the training environment should be designed as immersive, replicating the actual operating room and all the surrounding experiential elements, whenever possible. This includes replicating the visual components, the auditory effects of medical machines, and the haptic feedback that is critical in such contexts. As a result, learners immersed within such an environment would enjoy an authentic learning experience that carry over what they learn to the actual operating room.

8.2.8 Humanoid-based instructors

A novel approach that can be suitable and valuable for learning is by considering humanoids as teachers. This is especially important with the lack of skilled human instructors. We encourage designers of immersive learning environments to seek such smart robots as they can successfuly assume the role of instructors for many educational tasks.

Designers of future humanoid instructors may consider integrating machine-learning techniques for an improved learning experience. This dynamic capacity would enable a robot instructor to respond to some of the users' expectations and dynamically adapt to their skill levels. To address this desire and realize learning and outcome efficiencies, the system implementation should include smart decisions, and adjust the level of instruction relative to each learner.

8.3 Temporospatial Elements

Temporospatial elements represent a set of newly proposed concepts that relate to space and time and can be utilized in design to enrich interaction within 3D contexts [157]. We consider many of the aforementioned learning aids guidelines as temporospatial elements that augment user's interaction and the overall learning experience. Examples of such elements include providing user's with guidance trajectories, hinting at important changes to objects, and allowing the user to repeatedly train the task at hand.

In general, temporospatial design elements could be used to *signify* either virtual objects or the 3D-interaction techniques. In this regard, temporospatial elements are related to visual variables [30] and the concept of signifiers [172]. For example, designers may color a particular virtual object more reddish to highlight the object's temperature or render the object with transparency in order to hint at it representing a future possible outcome. Moreover, designers may integrate sound with the design of a travelling interaction technique to hint at its use or visualize the object only using outlines to indicate that it represents a context that is less important than other rendered objects. Such examples reflect how temporospatial elements augment user's awareness and guide interaction, ultimately enhancing the overall learning experience.

Three-Dimensional interaction techniques and temporospatial elements can be interlinked using the analogy of affordances [172]. Here, temporospatial elements would enable interaction with 3D objects by focusing more on representation of the techniques and the interaction possibilities (e.g., the ability to interact quickly/slowly) and how users would perceive these possibilities (i.e., perceived affordances). Another example is when user's interactions are captured over time and presented as intuitive history visualization allowing the user to manipulate time and try alternative interaction trajectories from the past.

Below is a list of some of these elements with a brief description of each:

1. Continuity: An affordance (between a user and an interaction technique) that refers to implicit succession of moments or events as well as connectivity of neighboring spatial blocks/locations (i.e., no discretization). Basically, it reflects that an interaction should continuously be performed without pausing.

2. Order: An affordance that reflects a particular arrangement of blocks or events, and that an interaction should be performed in a specific sequence. This unique element can be used to manipulate the sequence of events/actions to draw attention, to set and emphasis, to introduce different explanations for events, and to highlight the small differences between fiction and reality.

3. Velocity (i.e. rate, frequency, or rhythm): An affordance that relates speed of interaction from the temporal perspective to distance of interaction from the spatial perspective. Other special versions of the velocity element are “Scale” and “Pause”. The scale element may reflect the possibility of positively or negatively changing the resolution of space/time, e.g., an interaction can be performed slowly over a magnified area. The related affordance of pausing referring to having a void space and/or zero time would indicate frozen simulation as if the clock has stopped. An example of temporal distortion as unique interaction opportunities of this affordance is to slow down a complex process allowing the user to better grasp its dynamics

4. Shadowing: An affordance that reflects space cloning or time travel. In this regard, an interaction can be duplicated for unique experimentation, e.g., a user can clone the current interaction scenario as a snapshot to experiment with before actually deciding to commit to completing the interaction. “Repetition” is a form of shadowing wherein the intention is to

perform the same action multiple times. Noteworthy, this element can be highly valuable for supporting repetitive practice and training.

5. Trajectory: A signifier that reflects a path which exists in (3D) space suggesting a set of anticipated interaction possibilities. It can also support user's guidance towards what to do.

6. Sound: A signifier that could augment a particular spatial location with a changing rhythm, e.g., directing a user's attention during an interaction

7. Vibration: A signifier that could reflect physical tactile changes over time that occur to a particular object in space. The rate of the vibration and its focus characterizes the intended signification, e.g., to guide the user interaction towards a particular direction

8. Motion/Animation: A signifier that reflects an explicit changing in an object's appearance over time (e.g., an object's transparency over time indicates that it will disappear soon encouraging the user to engage with it quickly)

9. Transience: A (temporal) signifier that reflects an implicit changing (of space or an object's appearance) over time, e.g., Windows desktop tiles. Of note, transience may not necessarily be a temporospatial signifier as it may not reflect any connotation to space (e.g., as reflected in music). In addition, transience does not only relate to objects, but may also refer to morphing/deforming a spatial object over time. When combined with animation, it can hint user's attention to important changes such as blinking defective objects.

It is worth noting that other elements (i.e., visual variables) including Color, Size, Position, etc. reflect spatial signifiers/affordances that can enrich the representation of data and interaction. In 3D-spatial interactive immersive contexts, we consider all the aforementioned temporal and/or spatial elements that enrich user experience as temporospatial learning aids.

In summary, the results of our prototypes highlight the value of educational aids and how they have the potential to mediate experiential learning in immersive environments. We do not call for designers to follow these aids blindly in their designs of immersive learning systems. Rather, we argue that a re-visitation of such educational aids could be helpful in facilitating learning and imporving the overall learner's experience.

Chapter 9

Conclusion and Future Work

In this thesis, we presented our research on educational aids and how they can mediate experiential learning in interactive immersive environments. A potential for enriching educational and training experiences have been shown through the design, development and evaluation of four prototypes, and it is supported by insights we gained from users' feedback. The first prototype, *NeuroSimVR*, is a stereoscopic visualization augmented with learning aids to support how medical users learn about and experiment with a common back surgery procedure. The second prototype, *ReflectiveSpineVR*, is an immersive virtual reality surgical simulation with innovative interaction history capabilities that aim to empower users' memories and enable deliberate repetitive practice as needed. The third prototype, *JackVR*, is an interactive immersive training system, utilizing novel gamification elements, and aims to support oil-and-gas experts in the process of landing oil rigs. Finally, our fourth prototype, *RoboTeacher*, involves a humanoid robot instructor for teaching people industrial assembly tasks. In our prototypes, we presented novel learning aids, visualization, and interaction techniques that are new to many of the current immersive learning tools. We also presented a framework with theoretical insight into learning including guidelines and perspectives for future design efforts of building immersive learning environments. To summarize, the contributions of this thesis were:

1. **Deeper theoretical insight and better understanding of how educational aids and temporospatial elements can be incorporated into a three-dimensional context.**
2. **Design, development, and evaluation of a 3D simulation prototype aiming to facilitate learning of a specific back-surgery task. This includes simplified interaction capabilities and novel features (i.e., landmark trajectory hinting, step-by-step guidance, post-simulation feedback and 3D/haptic interfaces).**

3. **Design, development, and evaluation of a fully immersive surgical training prototype. This includes novel interaction history capabilities to support repetitive practice as a key element in surgical-based training. This project follows the insight of a design study that explores nonlinear interaction history representations and their potential as effective educational aids.**
4. **Design, development, and initial evaluation of an immersive virtual reality prototype aiming to simplify learning and experiencing the process of landing oil rigs. The implemented prototype replicates a dynamic and complex environment, simulating weather/sea conditions and including novel features (inspired from games).**
5. **Design, development, and evaluation of a humanoid-based prototype reflecting how robots can be instructors teaching industrial assembly tasks. This is especially valuable when there is a lack of human mentors or because of environmental challenges.**
6. **A summary of lessons learned and reflections that could guide future research efforts involving learning aids. This includes a set of temporospatial design guidelines and heuristics tailored to mediate experiential learning within immersive environments.**

9.1 Future Work

Our previous discussion of the design, implementation and evaluation of each of the presented prototypes highlighted suggestions and ideas for future directions (see Sections 5.2.3, 4.5, 6.5, and 7.5. Here, we present a more general broader future work discussion related to the elements shared among all our presented prototypes, namely, individualized independent learning (Section 9.1.1) and in-the-wild evaluation (Section 9.1.2). We also highlight a potential future direction for exploring the practicality of our non-linear interaction history representation in other contexts (Section

9.1.3)

9.1.1 Individualized Independent Learning

Teachers and trainers have always been key important elements for the success of learning. Indeed, most learners today depend on having a mentor or an effective simulation in order to learn certain topics or skills. However, it is still unclear how to address the lack of skilled instructors and how to better design learning environments with essential educational aids. Our research is a starting point to the vision of future immersive learning environments. In such systems, learners can independantly learn and are enriched with simplified interactions and immersive quality learning experiences. We argue that this vision would be applicable in the near future with the advancement in immersive technologies. Therefore, we call for design efforts towards supporting next-generation learning; that is, to enable an engaging, immersive, interactive, reflective, and learner-centred environments. It is worth noting that an interdisciplinary effort would be needed to achieve such quality learning experiences.

A crucial question to be answered is how to enable truly experiential learning that takes into consideration learners' knowledge and skills, and which adapts to the learning content autonomously. One idea toward solving that question could include examining better ways of collaboration between education experts and interaction designers, seeking an innovative approach to creating learning material and re-defining the role of teachers and immersive technology in that new space.

9.1.2 In-the-Wild Evaluation

We developed and evaluated most of our prototypes continuously guided by our domain collaborators. However, within the time and limitations of our work, we were only able to conduct preliminary formal evaluation studies with domain experts. Therefore, we think that future efforts are called for conducting detailed in-the-wild evaluation studies, thoroughly assessing the validity of the presented techniques in a more comprehensive way (e.g., task-oriented scenario). For example, our surgical simulation prototypes (from Chapters 4 and 5) could benefit from integration into an actual surgical education class as well as a comprehensive evaluation by additional medical residents and surgeons. Similarly, our oil-and-gas immersive training prototype, from Chapter 6, could benefit from a formal study involving a variety of domain engineers to assess its practicality, especially when compared to the current tools used by the experts. Finally, it can be helpful to integrate our RoboTeacher system (from Chapter 7) into an actual industrial assembly line and explore first-hand how it could facilitate the learning of novice trainees. We anticipate valuable feedback and insights from the in-situ evaluation of the aforementioned prototypes and therefore consider it to be a core part of our future work.

In spite of the fact that we took inspiration from the method of participatory design to involve potential users in the development process, we think that a comprehensive in-the-wild collaboration involving detailed studying of existing systems would be essential to truly assess the practicality of our approach and how it may support learning. Generally, future efforts aiming to extend this work could benefit from field observational techniques, and perhaps would enable better understanding of experts' needs.

9.1.3 Reflective Learning for everyone, anywhere, anytime

We explored a novel approach to supporting users' awareness of their interaction history through what we termed, ReflectiveHUD, which we presented in Chapter 5. We argue that our exploration of this non-linear innovative interaction history representation enables medical learners to deeply reflect and learn from their own decisions. Here, we extend our argument and envision a practical use and potential of our approach into other contexts beyond the surgical domain. Indeed, we attempted one example application of our ReflectiveHUD approach to the immersive training context of cooking (See Section 3.4.1).

As a future research direction, we anticipate that applying the ReflectiveHUD representation in other practical (learning) contexts would provide a better understanding of how it may impact people's awareness and interactions. Future prototype explorations involving our ReflectiveHUD representation may include oil-and-gas training, immersive architectural design, virtual city planning, as well as other medical education tasks. In essence, we foresee the non-linear history visualization as a feature that could augment future interactive learning environments, supporting reflective learning for all users, anywhere, anytime. Finally, we encourage designers who intend to integrate interaction history capabilities in their designs to consider and build upon our approach and the reported feedback, in a hope to better enhance and adapt such reflective representation in future learning contexts.

9.2 Final Words

In this thesis, we presented our experimental research through a set of prototypes designed and developed exploring how learning can be enriched within immersive environments. Our prototypes combined with techniques showed the potential benefits of employing innovative learning aids towards enabling experiential quality learning experience. The outcome of the conducted evaluations reflected on how to further pursue this endeavor in the future. We also presented a framework involving a set of recommendations reflecting on different aspects of our work, and providing a concise set of suggestions aiming to support future research involving the design of immersive learning environments. While there is a wide scope of future efforts to explore different forms of designing immersive learning environments, we hope that our research will shed new light and inspire future research directions leading to better solutions in this important topic.

Appendix A

Domain Background

A.1 Oil and Gas

In general, the oil-and-gas domain can be divided into two sub-domains, geology and reservoir engineering. The geology reflects the sedimentology and rock structure and attempts to analyze and understand the behavior of changes to rocks over the years. Reservoir engineering comes later and focuses on flow simulation. The analogy here is with human body where the body structure (e.g. bones and cells and the changes to them as we grow) is the focus of geology while how the blood flows is the focus of reservoir engineering.

Reservoir Engineering Simulation

Oil reservoirs represent underground volumes of hydrocarbons. Reservoir engineers model and study their reservoirs to optimize hydrocarbons extraction [39]. In this domain, one of the main goals is to provide, as accurate as possible, a representation of the reservoir model that typically represents a set of cells arranged in grid formation (Figure A.1). Each reservoir cell can represent the parameter values for one or more properties. For instance, a cell may represent static information regarding the rock formation (e.g., porosity and permeability) as well as dynamic information such as the estimated value of the flowing fluids (e.g., the rate of water or oil passing through). Engineers attempt to achieve such accurate representation of the reservoir model by continuously changing specific properties (e.g., oil saturation) or modifying boundary conditions (e.g. injecting water at certain locations) and re-run the simulation. Such changes affect the underlying reservoir structure and the movement of oil. This process involves a lot of uncertainties. In addition, experts only depend on statistical analysis and primitive visualization to monitor the dynamics of the reservoir model.

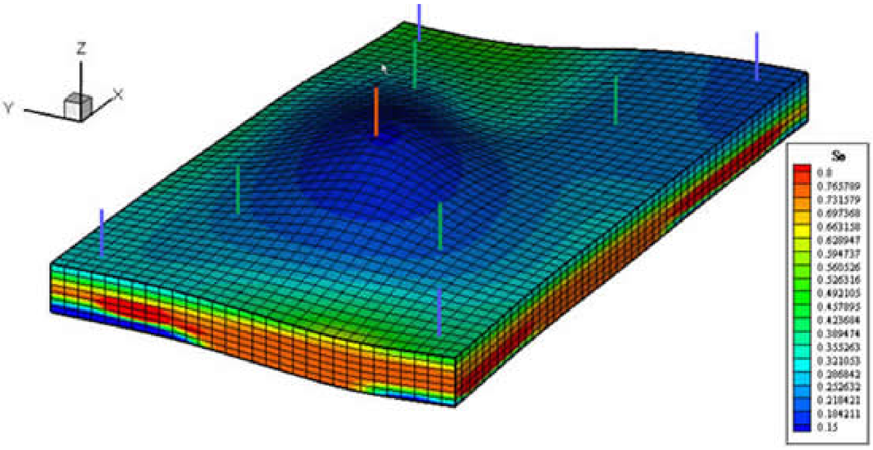


Figure A.1: Representation of a reservoir engineering model depicted as a set of cells

Landing Oil Rigs

Drilling is one of the main processes in hydrocarbon extractions with onshore or offshore drilling units. The offshore rigs are mounted mostly in the middle of the ocean wherein the goal is to prepare a fixed platform to support drilling and extraction of oil stored under the seabed. Jackup rigs [189] are among the most common offshore drilling units due to their low operation and maintenance cost, with the assumption that they sustain the harsh conditions of the weather and the sea. A jackup rig usually consists of the rig itself, the legs, spud cans (heavy objects attached to the legs to facilitate seabed penetration), and the hull (Figure A.2). The legs and the hull of most jackup rigs usually can be lifted down/up through the rigs' jacking system. The weight of the jackup rig impacts the landing at certain points and proper utilization of the rig's hull with the water level inside the hull must be maintained. The stability of the rig mostly depends on the rig's weight and the environmental forces applied (e.g. wind and ocean pressure).

A.2 Surgery

Simulation and virtual reality has proven to be effective to improve surgical training [58]. In this regard, virtual reality systems are designed to support a particular training objective. For instance,

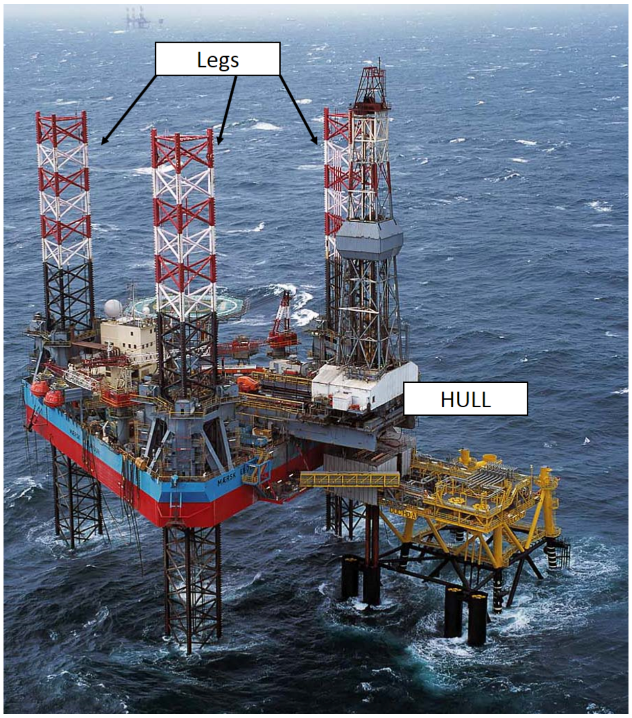


Figure A.2: Jackup Oil Rig mounted in the middle of the ocean

surgeons/residents often need adequate training of psycho-motor skills that are critical in almost all surgical tasks. Therefore, many simulation systems aim to support training of such skills through multiple simplified tasks (e.g. Pick and Place, MatchBoard, Pig Transfer, etc), allowing users to practice in a safe and low-cost environment. Another learning objective of training in surgery is to improve the surgeon's ability to react and make decisions. This can particularly be useful in handling unexpected situations that may arise during surgery (e.g. the patient's heart stopped). In this section, we overview the procedures of aneurysm treatment and pedicle screw insertion for their relevancy to our explorations in this disseration.

Overview of Aneurysm Treatment

Aneurysm represents a weak point in a blood vessel wall in which the blood bulges out in a way similar to ballooning (Figure A.3). Based on the size and shape, a brain aneurysm can lead to a leak or rupture of the blood vessel resulting in grave consequences, including death. Surgical intervention is one of the main modalities in managing aneurysms [241]. This procedure usually

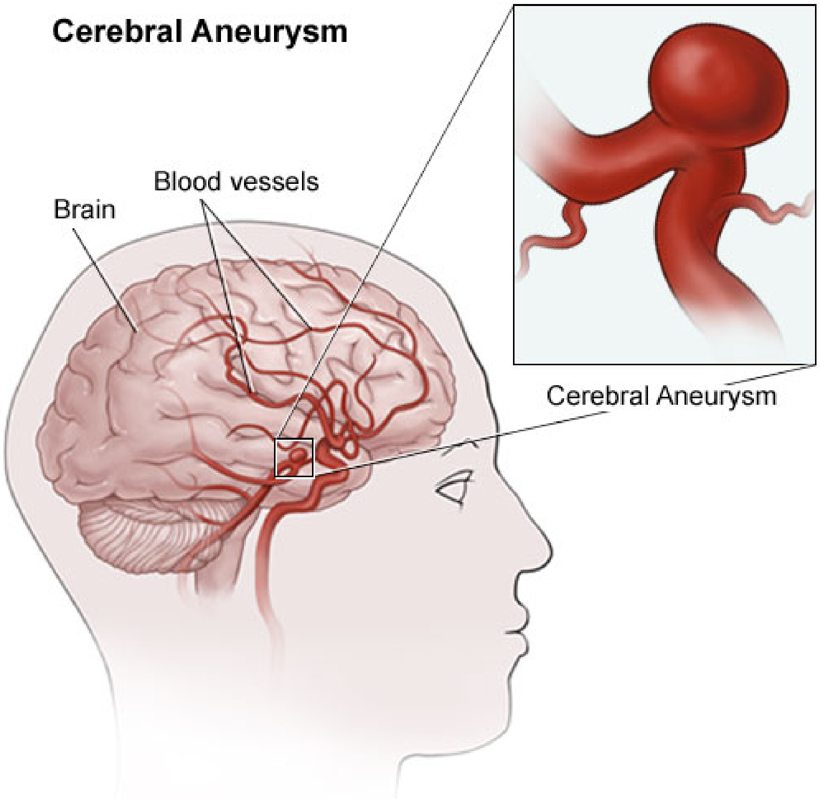


Figure A.3: Illustrative of Brain Aneurysm as a weak point in a blood vessel wall

involves putting a clip across the weak blood vessel wall. Below is a simplified description of the steps involved in this treatment.

Generally, the surgeon has to use medical tools to reach the location of the aneurysm and clip it. Thus, the skull is cut open and the brain tissues are moved apart to expose the aneurysm. Then, a surgical clip is placed around the aneurysm base. As a result, the aneurysm is no longer available for blood entry. However, in case of bleeding, the surgeon must react immediately and treat the aneurysm by clipping, while correcting the vital functions such as breathing and reducing pressure within the brain.

Spine Surgery & Pedicle Screw Insertion

A human spine is composed of various vertebra levels that are grouped to cervical spine, thoracic spine and lumbar spine. The pedicle screw insertion task is common in any of these spines with difficulty that varies accordingly. For effective task completion, knowledge about the anatomy of the spinal area is needed. The unfortunate mistake by any medical surgeon during such a surgery may leave the patient paralyzed or at the least destroy the spinal bones, a problem that is mostly irreversible. Therefore, there is a strong need for safe and cost-effective simulation environments to train the medical surgeons of that procedure.

Surgeons usually need to go through many steps to complete the surgical procedure of Pedicle Screw Insertion (PSI). However, we only overview key relevant steps here for convenience reasons (for detailed procedure description and workflow please see [166]). First, the surgeon attempts to identify landmarks or entry points for screw insertion to support particular vertebrae, guided by x-ray images and using his or her understanding of the specific patient anatomy. Then, the surgeon drills carefully and makes pilot holes over the previously identified landmarks. Finally, screws of particular size and diameter are placed in the created holes. This simplified description of the task requires knowledge about the anatomy and mental reconstruction of all the things that could go wrong including touching a nerve (i.e., neurovascular injury), misplacing the screw so that it skips the bone, or creating a hole wider than needed. Therefore, medical practitioners would benefit from the ability to learn about and train the PSI procedure through an immersive surgical simulation prototype.

A.3 Robotics

In general, a robot is a machine that can perform complex series of actions autonomously [243]. Robots, in most cases, are designed with an arbitary shape with some of them taking a human form. They are often controlled externally by a device or they may have the control embedded within. Robots can be autonomous or semi-autonomous and range from humanoids to industrial robots, medical operating robots, UAV drones, among other types.

Robots have replaced humans in performing repetitive and dangerous tasks which humans prefer not to do, or are unable to do because of size limitations, or which take place in extreme environments such as outer space or the bottom of the sea. With the increasing use of robots in today's socities, there are concerns about their role as they replace workers in increasing numbers of functions, which caused some to blame them for rising unemployment.

Humanoid Robots

A humanoid robot is a robot with its body shape built to resemble the human body (Example of Baxter in Figure 7.2). The design may be for functional purposes, such as interacting with human tools and environments, for experimental purposes, such as the study of locomotion, or for other purposes. In general, humanoid robots have a torso, a head, two arms, and two legs, though some forms of humanoid robots may model only part of the body, for example, from the waist up. Some humanoid robot also have heads designed to replicate human facial features such as eyes and mouths. Androids are humanoid robots built to aesthetically resemble humans

Appendix B

Designing Virtual Experiences Based on a “Superhumans” Metaphor

Virtual environments (VE) allow people to interact in ways which are beyond their human capabilities. Various elements are needed to ensure a believable VE experience including high-fidelity graphics, rich sensory feedback, and an engaging storyline. However, adding these elements up does not necessitate an effective or satisfactory user experience, and can still leave users unaware of what can be expected exactly from their VE experience. We propose a design metaphor we call superhumans that can empower 3D interaction designers to create and implement interactive mixed and virtual reality environments, and to help users familiarize themselves with interactive VE capabilities, behaviour and limitations [155]. We describe how the superhumans metaphor supports VE designers and allow them to align the user experience they create to specific features of the immersive experience. We also explain through a set of examples how the superhumans design metaphor can be applied to practical VE applications.

B.1 Introduction

Even after decades of research and practice in the domain of virtual environments (VE), designing an effective and engaging VE remains a challenging task, and the search for a “killer app” is still ongoing. Considerable efforts are being focused on improving the technology supporting the VE experience, or on reducing its cost. Arguably there is less focus on how to match the VE experience with people expectations, and on design methods that would allow harnessing the VE technology to effective and satisfying user experiences. We see VE as another step in a continuum of creative mediums, such as storytelling, literature, theater and film. These classic creative medium practiced to perfection ways of engaging people in the experience they afford. Our research explores better ways of leveraging this previous knowledge when designing VE experiences. We focus on a specific thread within this larger theme, exploring how VE designers can take advantage of a superhuman metaphor. People reflected on superhumans abilities throughout the documented history via every possible creative medium [201]. These reflections inspired new ways of thinking on humans' limitations, on how to confront challenges and on how to aspire to improve and advance our earthly human existence.

Beyond its rich history in classic creative mediums, superhumans seem to address many of the inherent capabilities of VE, which is often designed to create immersive experiences that allow users to step out of their physical limitations and to experience sensory reflections that are well beyond what they are capable of physically. Our goal is to adopt the superhuman metaphor for the design of VE, creating a design framework that will help align the specifics of the immersive experience with users' expectations. To achieve this goal we propose using various design elements emerging from storytelling and game design, and present preliminary results of our attempt of applying and evaluating the superhumans metaphor in a set of preliminary scenarios.

B.2 Related Work

The design of VE and 3D interaction techniques was often inspired and motivated by metaphors from either real or magic realms [23]. While common in film and gaming applications to adapt metaphors and design elements based on existing ideas, few works considered the use of design metaphors in VE beyond the specifics of a task. Disney's Aladdin by Pausch et al. [179] is an early work which allowed users to experience flying a magic carpet through a virtual world based on the animated film "Aladdin", highlighting the importance of seeing beyond the technology and onto the content and story. A more recent work by Roussou [197] argued that interactive VE tend to focus on the construction of objects and spaces, but less on stories that tie them together. Hill et al. [221] explored a holodeck prototype by integrating various sensory elements (i.e. audio and story).

The authors reported that the audience was willing to suspend disbelief (even with many technical imperfections) and that the overall experiment was worth the integration. More recently, Lindeman and Beckhaus [132] discussed experiential fidelity as a new approach to how memorable virtual experiences could be created. Closely related, Sproll et al. [212] attempted to consider aspects of transitional environments by proposing a framework to facilitate transitioning into virtual reality. Most recently, a study by Rosenberg et al. [196] aimed to measure whether having the superhero ability of flying within the VE would encourage prosocial behavior or not, and their goal was to explore how giving participants an enhanced ability in the VE may affect helping behaviour after they were out of the VE experience. Our initial exploration follows the aforementioned works and aim to provide a holistic approach to designing virtual experiences with additional focus on the content

B.3 The Superhuman Metaphor

In this section, we present our initial attempt of exploring the superhumans design metaphor as a convention to support the design of virtual immersive applications [155].

We see the superhumans metaphor particularly related to user awareness of the VE capabilities and interactions. We envision that the user-awareness could be enhanced via a set of transformation elements (perceptual motivations and gamification aspects) in order to transform users as super-humans within the VE world. A Car, for example, is technological entity that empowers people to travel faster than their innate abilities. When a 21st century person enters a car they expect to travel faster than what they could using their feet. Similarly, the superhumans design metaphor encourages users to imagine themselves as being empowered with superhuman abilities, and to expect a corresponding transformation when they are about to participate in the immersive experience.

We claim the following: the more the user is aware of what to expect within the VE and about its capabilities, the better he or she will be in achieving the intended tasks. For that, the superhu-

Figure B.1: Schematic overview of the process of microseismic monitoring

mans metaphor suggests building various levels of awareness and supporting corresponding interactions for the coarse of the VE experience. In this regard, a continuum going from fully-aware (transformed) user to fully-unaware (untransformed) user, can be used to describe how various users interacting within the VE may have various awareness levels (Figure B.1). These transformations may happen mentally by motivating the users via narration or storytelling, or physically through empowerment elements, such as wearing superhero clothing, taking superpower pills, or by adaptation of transitional environments (e.g., Portals [216]).

Applying the superhumans metaphor reflects a structure of three phases. The first phase is about a pre-immersion stage which focuses on preparing the users prior to any engagement with the VE, and this might include physical/mental transformations as needed. For example, the environment setup could involve specialized preparations similar to visualization rooms but with additional elements (i.e. suitable sound and lighting setup to the VE theme). In the second phase, during the immersion, transformation elements should be continuously triggered to help the users retain the context and ensure that the suspense of disbelief is maintained most of the time. For example, virtual characters should be carefully integrated in the VE and appear from time-to-time to guide users and keep them engaged. Finally, the post-immersion phase focuses on aspects which to be considered before ending the virtual experiences (and which may extend beyond it). For example, implementation of ways to transition-out the user seamlessly should be carefully integrated. In this regard, users are returning to reality and some of them may not be not willing to leave the virtuality side.

Designers of VE should think more about both potential users and the content of the virtual environment, as much as they think about having a successful technical implementation. Designers following the superhumans are encouraged to support seamless transitions among the various subtasks of the VE. This idea is similar to the concept of "cinematic director" that is used in film and theatre to smoothly shift the attention of the viewers. Cinematic directors update the scene with multiple effects (e.g., change in sound, lighting, etc.) to prepare for scene transitions. Along those lines, designers should adapt a similar approach to ease users into the next sub-task or interaction goal within the VE.

The superhumans is particularly related to the idea of constraints and how manipulating them would affect the design of VE applications. Bier [15] presented an example of applying constraints to manipulate the degrees-of-freedom in order to effectively enable interaction with 3D objects using the mouse. The superhumans metaphor, similarly, suggests minimizing the gap between reality and virtuality by adopting the nature of superhumans traits to allow users to engage with and experience a non-constrained VE. For instance, within the real world we can not fly or ignore gravity laws, but we can do that within the VE, and the superhumans metaphor suggests linking and relating these two capabilities together. In this regard, the concept of "portals" from film and story-telling could be considered as one capability to facilitate travelling within the VE in a more magical way. The superhumans, if applied, would unleash the constraints of flying/travelling, so the users within the VE will be motivated to create virtual portals at any location to travel to other destinations. Technically, these abilities would emerge from the VE's underlying computational capabilities. From the perspective of users, the superhumans metaphor provides a powerful mean justifying and explaining how the users gained super abilities with the VE.

In essence, the superhumans metaphor as a framework may include, (1) a backstory, (2) an introduction to how the users are enabled to interact with environment (i.e. through superpowers), and (3) elements that help the users retain context while in the experience.

B.3.1 Superhumans and Game Design

Video games include fantastical things such as superheroes or visiting alien worlds. In addition, games are considered an example of how superhumans attributes can be assigned to a character. However, games are still mainly about fun and the level of immersion is much less in comparison to most VE applications. Interestingly, gamification [51] is a recent phenomenon that suggests using game-elements in non-gaming contexts, which is clearly applicable to the design of VE. In this regard, the superhumans metaphor will include description of aspects of gamification and their potential impact for the design of immersive virtual systems in order to provide a deeper experience that goes beyond fun, and to enable users to interact in original ways. Similar to designing games, VE designers are advised to consider inspiration and design elements from magic metaphors (i.e. fantasy novels) to enable users to explore beyond human abilities and limitations, thus unleash the true power of the virtual experience. For example, a user within the VE could be represented by a 3D human model, but his energy-level may be represented by a glow effect around his body similar to the visualization of Chakra within the metaphysical belief systems.

B.3.2 How This Can Be Applied?

In this section, we give an overview about how the superhumans metaphor could be validated through a set of demonstrated practical contexts. We use scenarios applied within specific domain contexts (i.e., training and oil-and-gas exploration). We describe the tasks as being performed by two different user-groups. The first group is given the ability to perform the tasks without employing the superhumans metaphor. Participants of the second group are empowered to act as superhumans while engaging with the tasks. Technically, the supported interaction capabilities are the same for both groups. The major difference is perceptual and would be defined through the level of user-awareness.

Training Disabled People On Driving

For the first training scenario, we envision how the superhumans metaphor could help newly disabled persons (after an accident) on how to drive a wheelchair. In this regard, such disabled persons may be embarrassed to fall down or drive the wheelchair in certain places such as crowded streets. A virtual environment to assist these persons is a valid and needed training application.

The poor design of immersive training application for disabled users may be considered uncomfortable to them especially if they are unfamiliar with the hassle of technology. By applying the superhumans metaphor, this training system can be designed and introduced with many motivation elements to empower the (disabled) users of it. A traditional design would allow the user within a simulation environement to drive a wheelchair and be trained to handle various situations including busy streets. When applying the superhumans metaphor the system could adapt a story-based approach to engage users. Furthermore, transitional elements could be integrated to simplify switching from reality to virtuality and vice versa. Also superpower-inspired interactions could be added to empower users to interact in new ways and even enjoy the training.

Fixing A Broken Network

In the second training scenario, consider a technical support expert who, for instance, has to move periodically between various floors of some building in order to fix a networking issue as part of his job. In one case, he is working to fix the internet connection of some user in the 7th floor. However, he needs to move back and forth between the main floor and the 7th floor while trying some configurations, which are necessary for testing the network. Interestingly, sometimes the network cables are hidden or broken, so the technical support expert needs to further inspect tools to check cables connection across multiple floors.

Simulating this scenario using a traditional immersive interface would include various interactions. For instance, the user can test specific floors by travelling from one floor to the next, which would usually take the form of sudden jumps initiated according to user's commands. The design could also provide capabilities to test specific cables one by one, and report which one requires attention due to some issue. When such experiment applies the superhumans metaphor, the user involved could be motivated with knowledge about the system's expectations and interaction capabilities as a superhuman. In this regard, the user will know that he can activate certain superhuman powers during the task; he would know that he can time/space travel to any other floor by using his superpowers by creating movable portals that would take him to new destinations. Consequently, the transition is much more suitable for the magic of the immersive experience. Similarly, the user can activate his super-vision power to discover cable issues directly. Thus, all broken cables that require attention will be highlighted with superimposed information depicting their status.

Balancing Underground Injection of Chemical Fluids

Another scenario from the oil-and-gas domain is microseismic monitoring. This process involves injecting fluids in the underground through an injection-well to assess certain aspects of the oil reservoir (Figure B.2). The visualization shown includes various potential elements for interaction such as the 3D microseismic events and the surrounding environment objects (e.g., monitoring wells, reservoir layers, sensor geophones). The user of an immersive visualization of such scenario needs to navigate the 3D environment (using free camera) with the ability to control the speed of the navigation, as needed. Also, the user may need to travel from the earthlevel to the deep rock-layers of the reservoir by specifying an interface command that changes the view to the required reservoir location. Furthermore, sometimes the user wants to filter the data and only focus on a subset that resembles high-magnitude events. For that, the user needs to activate the proper user-interface commands to only show those events that satisfy her needs.

Exploration of microseismic data is not straightforward and requires certain skillset. Microseismic engineers are likely to experience a more intuitive interaction when the empowerment of the superhumans metaphor are employed. In this case, a user will be empowered as a superhuman with various superpowers prior to engaging with the immersive visualization. The user will expect that she can fly-around freely and that she is capable of adjusting her size to fit between rock layers. She might also create movable portals to seamlessly travel from earth-level to any reservoir depth without sudden changes. To filter the data, the user would activate her super-vision ability to look for high-magnitude events which will be highlighted automatically when she looks at them. Finally, the user may use her superpower to emit freezing energy and balance the injection of fluids, as needed (as shown in Figure B.3)

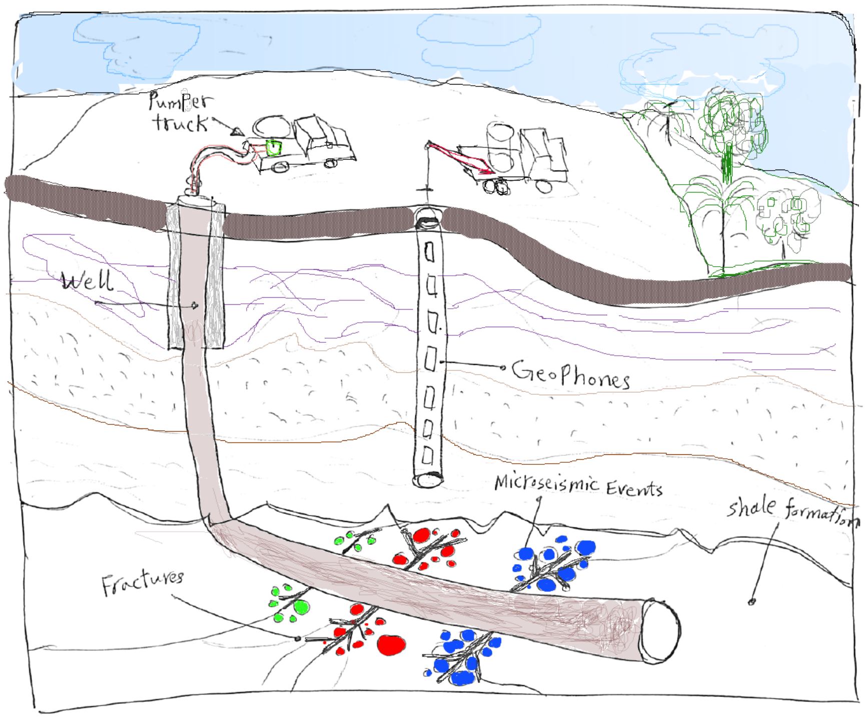


Figure B.2: Schematic overview of the process of microseismic monitoring

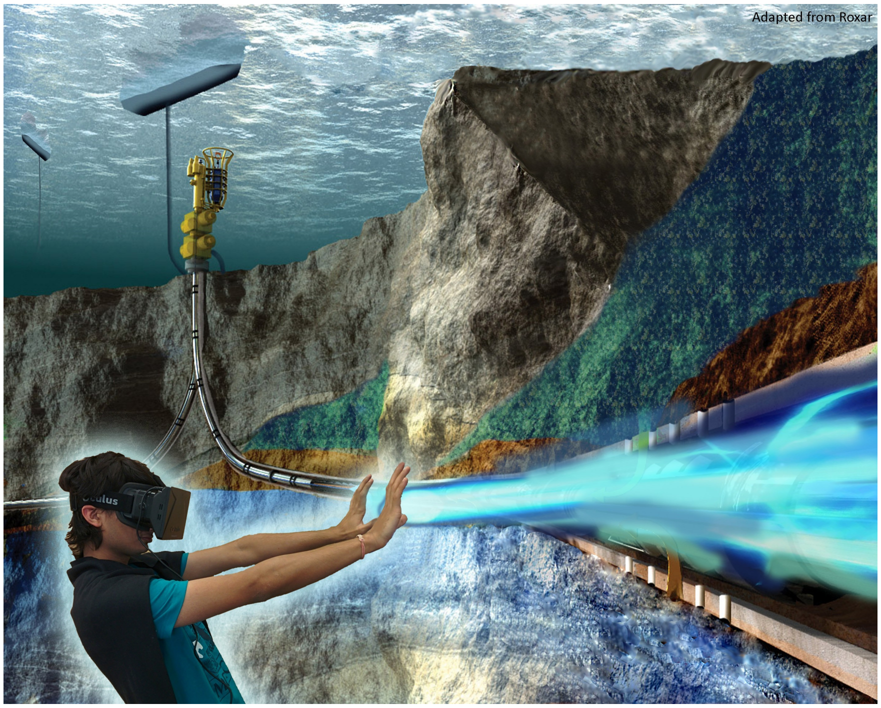


Figure B.3: Illustration of how a superhuman user can engage with operating a fluid injection well underground

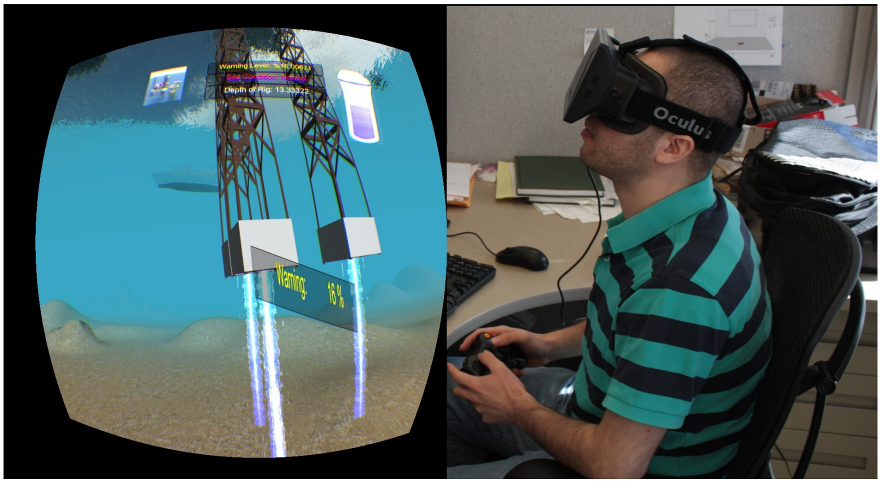


Figure B.4: Overview of a user engaged with a VR training system for oil-rig landing, in the "superhumans" mode

B.3.3 Preliminary Evaluation

In this dissertation, we have prototyped a virtual reality training system for the process of landing oil rigs in oceans. Landing an oil rig is an important task that involves many uncertainties due to the nature of the environmental conditions. Furthermore, a failure in the landing process could impact the geometry of the seabed and cause high economic loss. In our implementation, which is detailed in Chapter 6, we applied the superhumans metaphor to enrich users within the virtual environment. Users are allowed to engage with the simulation through either normal or a superhuman mode. When engaged in the normal mode, users receive less empowerments while still being able to completely control all aspects of the training. Through the superhuman mode, on the other hand, users are empowered with the ability to fly-around, and also with supervision abilities to see superimposed visualizations about the simulation (Figure B.4).

We present the preliminary feedback we received from having three design critique sessions with a domain expert (reservoir engineer). Our participant showed interest about the idea of superhumans. After trying our simulation, the expert expressed: "It was beneficial to have an immersive pre-session for overviewing the task and what to expect. It could also be helpful to have it with a recorded voice or a text on-screen or both of them". Such simple feedback highlights the potential of how applying the superhuman metaphor may be helpful in practical contexts.

B.4 Conclusion

We presented our attempt to detail the superhumans design metaphor, which aims to enrich the design of virtual environments. The metaphor encourages supporting a set of super-humans, physical and cognitive, capabilities to inspire designers and empower end-users within the VE. When applying the metaphor, various transformation elements should be considered including inspirational sources supporting the specific superhumans capabilities to avoid nullifying the virtual experience. The structure of the metaphor revolves around three phases; before, during, and after engaging with the immersive experience.

Appendix C

Introduction to Temporal Distortion

Time is something people understand intuitively but cannot manipulate. Surprisingly, the linear aspect of time could be distorted, or at least perceived as such. Research in psychology temporal design includes examples of such attempts to explain our perception of time and how it may be distorted (e.g. [138] and [60]). Motivated by how immersive virtual environments enable people to experience things beyond reality, we explore temporal illusions including why and how the distortion of time may be beneficial especially within immersive learning environments.

C.1 Background

Our perception of time is reflected in many discussions over the years by researchers from different fields (e.g., [128] and [108]). For detailed review, please refer to Section 2.7 in the background chapter of this dissertation.

In psychology, a temporal illusion is a distortion in the perception of time and is subjectively reported. Most studies focus in attempting to understand why we perceive time differently during certain moments (e.g., a life-threatening event). For instance, the research conducted by David Eagleman established that time does not actually slow down for a person during a life-threatening event but, rather, it is only a retrospective assessment that brings about such a conclusion [60]. He measured time perception during free-fall by strapping palm-top computers to subjects' wrists and having them perform psychophysical experiments as they fall. By measuring their speed of information intake, he concluded that participants did not have increased temporal resolution during the fall but, because their memories are more densely packed during a frightening situation, the event merely seems to have taken longer.

In the popular essay "Brain Time" [59], the author explains that different types of sensory information (auditory, tactile, visual, etc.) are processed at different speeds by different neural architectures. The author stated, *"The brain must learn how to overcome these speed disparities if it is to create a temporally unified representation of the external world: if the visual brain wants to get events correct timewise, it may have only one choice: wait for the slowest information to arrive. To accomplish this, it must wait about a tenth of a second. In the early days of television broadcasting, engineers worried about the problem of keeping audio and video signals synchronized. Then they accidentally discovered that they had around a hundred milliseconds of slop: As long as the signals arrived within this window, viewers' brains would automatically resynchronize the signals."* He goes on to say that *"This brief waiting period allows the visual system to discount the various delays imposed by the early stages; however, it has the disadvantage of pushing perception into the past. There is a distinct survival advantage to operating as close to the present as possible; an animal does not want to live too far in the past."*

Researchers have explored various types of illusions of time including manipulating order, simultaneity, repetition, motion, and frequency. In one experiment, subjects played various forms of video games. Unknown to the participants, the experimenters introduced a fixed delay between the mouse movements and the subsequent sensory feedback. This affected how the subjects adapted to the delay and later the lack of it [217]. In another work, subjects perceived the first of a sequential train of identical flashes of light to last longer than those in the middle of the train [195]. Motion also could be designed to manipulate our perception of time. This was demonstrated in a classic study where subjects reported the duration of moving stimuli to last longer than stationary ones [26]. Similarly, the frequency of simuli can impact our perception of time. In other words, apparent duration of a visual event increases with increasing the temporal frequency of it [112]. It is worth noting that our perception of these illusions may be affected by induced motivation. For instance, we may perceive temporal length of a given task to be shorten with greater motivation. The goal of this research is to explore how one or more of the aforementioned illusions could be utilized in virtual immersive environments.

C.2 Distorion of Time

In this section, we discuss the potential and importance of the distortion of time as well as common ways to achieve that.

C.2.1 Why

Designing for temporal illusions could have various benefits particularly for training and education purposes. For instance, it could support skill training when the user fails multiple attempts. Here, the system design may slow time progressively as needed allowing the user to improve skill and gradually succeed.

The ability to make time slower or faster is an interesting learning aspect that proved valuable in how people experience the psychology of time, as demonstarted in this dissertation. We argue that the distorion of time could particularly be useful in scenarios where realism is less important than supporting flexibility and creative learning. It is note worthy that our ideas are in line with Bret Victor explorations on time abstraction [230].

Manipulating time could also facilitate how users interact with complex simulations, by setting expectations and showing trajectories of possible interaction capabilities. Along the same line, games and entertainment have shown great potential for time manipulations by allowing players to travel in time and slow actions down, as needed. Examples of such games include Prince of Persia, Max Payne, Braid, and Quantum Break.

C.2.2 How

Our exploration of temporospatial elements (in this dissertation) is one example of how to design for and enable temporal distortions. In general, we argue that immersive environments have great potential to exploring temporal distortions as they allow users to experience unrealistic interactions.

Beyond giving users explicit ability to control time (e.g., a slider to make time slower/faster), we encourage designers to consider manipulating one or more of the following temporal illusion elements in their design: order, simultaneity, repetition, motion, and frequency. For example, designers may develop the system with automatic time scaling that manipulate the speed of interactions based on user skill/performance. Also, designers may decide to signal transitioning in time through visual/audial effects or subdivid the interaction space according to specific time connotations, where objects in certain areas are being simulated faster than others.

C.3 Illusion of Time in Immersive Environment

We replicated a psychological study on temporal distortion in a virtual reality simulation. Our goal is to explore how users in immersive environments may perceive the impact of motion on duration estimation, and how the immersive 3D visualization may contribute to that.

We based our prototype on the work of Kanai and others [112]. Due to time limitations, we only replicated the first experiemnt of the five original experiements the authors have performed.

The task was to reproduce the duration of a stimulus (represented as white 3D cube) by depressing the space bar on a keyboard after each stimulus presentation. During the reproduction period, only the fixation point was presented. One second after the key release, the next trial automatically started. No feedback was given to the observers. In the experiment, stimuli were presented for one of five durations (200, 400, 600, 800, or 1,000 ms) against a gray background. We receruited two participants where each completed 15 trials per condition (Figure C.1).

In our implementation, we used a moving or stationary black cube (3.2 3.2) presented for a variable duration (Figure C.2). The stimulus started moving from the position just below a well-defined fixation point (rendered as a 3D white sphere), which was presented 400 pixels (16) to the left of the horizontal center of the field of view. Participants were seated and oriented such that the fixation point appears directly in front of them. The velocity of the stimulus varied between 0, 2, 4, 8, 16, 24, and 32 deg/s. After each stimulus had disappeared, observers were asked to press and hold a key to reproduce its duration. For accuracy judgements, we varied the presentation duration between 200 and 1,000 ms. The amount of overestimation was calculated as the difference between

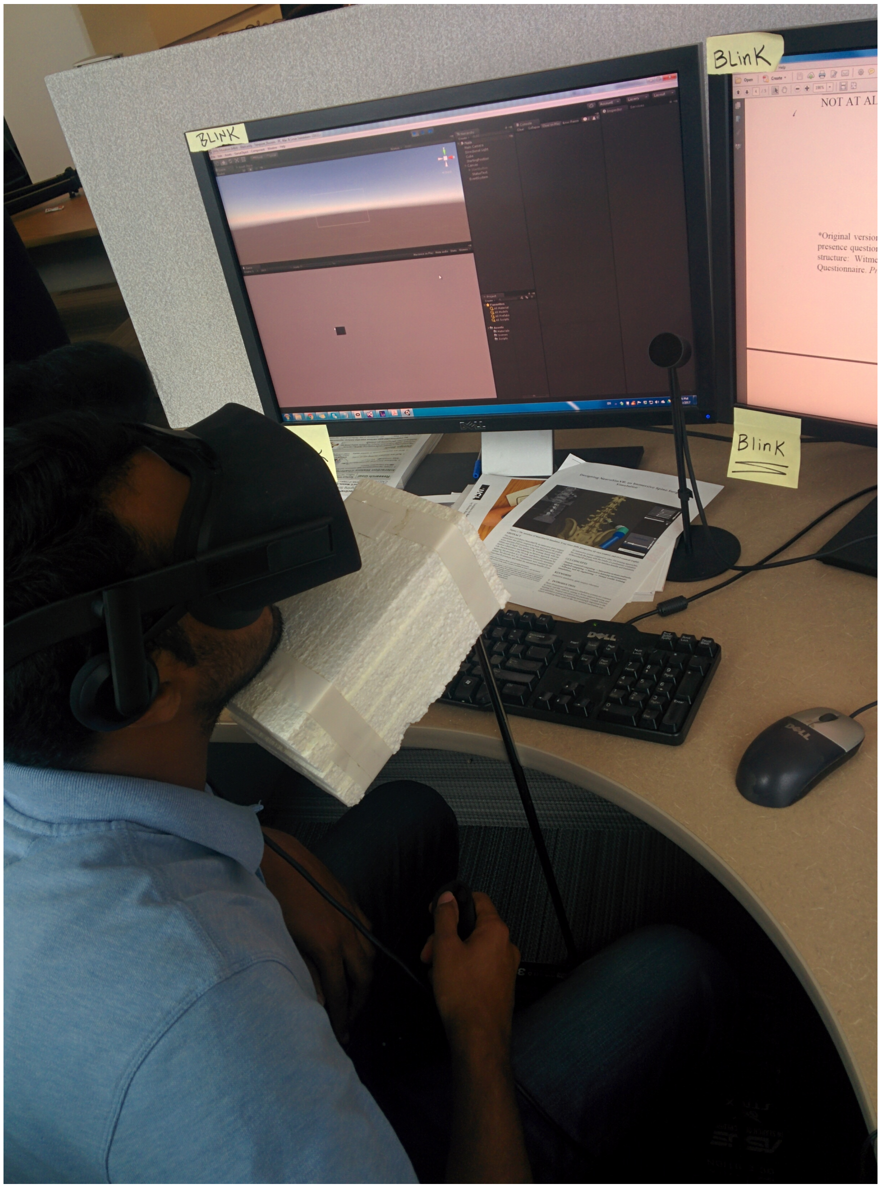


Figure C.1: Participant reporting the duration of a shown stimulus while using our immersive prototype.

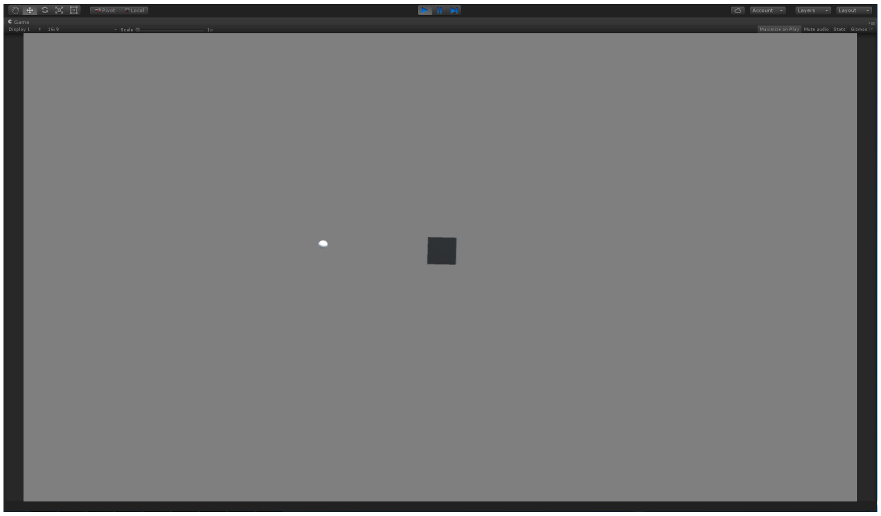


Figure C.2: Visualization of the stimulus each observer saw prior to estimating the appearence of its duration

the reported duration and the physical duration of the stimulus.

The data were collected as a CSV file per participants including reporting of their duration estimation as well as the actual duration of the stimuli. It is worth noting that our implementation was built in a generic way supporting replication of the other original experiments. However, we have not conducted these experiments and we did not analyze the collected data due to time limitations.

C.4 Conclusion

We believe that the presented initial exploration of temporal illusions could be a starting point for a future research. We argue that the potential of including temporal distortions in immersive system design has the potential to enrich user interactions, and would enable creative explorations beyond accurate simulation of tasks.

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