BUILDING LEARNER-CENTERED EDUCATIONAL EXPERIENCES IN VIRTUAL REALITY

By
Manshul Belani
(PhD17010)

Advised by
Dr. Pushpendra Singh (IIIT-Delhi, India) &
Dr. Aman Parnami (Ohilo, India)

A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy in the
Department of Human-Centered Design
Indraprastha Institute of Information Technology Delhi

December 2025

INDRAPRASTHA INSTITUTE *of*
INFORMATION TECHNOLOGY **DELHI**

BUILDING LEARNER-CENTERED EDUCATIONAL EXPERIENCES IN VIRTUAL REALITY

Thesis committee:

Dr. Arun Kulshreshth
(External Examiner)
School of Computing Informatics
University of Louisiana

Dr. Pushpendra Singh
(Advisor)
Department of Computer Science
IIIT-Delhi

Dr. Srinivasan Venkataraman
(External Examiner
Department of Design
Indian Institute of Technology Delhi

Dr. Aman Parnami
(Advisor)
Ohilo, India

Dr. Thomas Wischgoll
(External Examiner)
Computer Science Department
Wright State University

Date approved: 17 December 2025

CERTIFICATE

This is to certify that the thesis titled *"Building Learner-Centered Educational Experiences in Virtual Reality"*, being submitted by *Manshul Belani* to the Indraprastha Institute of Information Technology Delhi (IIIT-Delhi) for the award of the degree of Doctor of Philosophy, is an original research work carried out by her under the supervision of Prof. Pushpendra Singh (IIIT-Delhi, India) and Dr. Aman Parnami (Ohilo, India). In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results presented in this thesis have not been submitted in part or whole to any other university or institute for the award of any degree/diploma.

Prof. Pushpendra Singh
Department of Computer Science
IIIT-Delhi, India
December, 2025.

Dr. Aman Parnami
Ohilo, India
December, 2025.

CANDIDATE DECLARATION

The author hereby declares that the work presented in the thesis titled *"Building Learner-Centered Educational Experiences in Virtual Reality"*, submitted as partial fulfillment for the award of the degree of Doctor of Philosophy to the IIIT-Delhi is an original research work carried out under the joint supervision of Prof. Pushpendra Singh (Professor, Department of Computer Science, IIIT Delhi, India) and Dr. Aman Parnami (Ohilo, India).

The results presented in this thesis have not been submitted in part or whole to any other university or institute for the award of any degree/diploma.

Manshul Belani (PhD17010)

Department of Human-Centered Design

IIIT-Delhi, India

December, 2025.

ACKNOWLEDGMENTS

Bringing this thesis to life has been a deeply transformative journey that I could not have walked alone. I am profoundly grateful to all those whose support, inspiration, and belief sustained me through its many phases. This work is not mine alone; it carries the imprints of those who stood beside me, in ways both visible and invisible. Reaching this milestone fills me with immense appreciation for the many contributions that shaped both the thesis and my personal growth along the way. While it's easy to think of this path as a solitary struggle, I want to acknowledge that the weight of this journey was often shared, sometimes by choice, sometimes simply out of love and care by the people I will speak about in the following paragraphs. I owe each of them a debt of gratitude that words can only begin to express.

I remain profoundly indebted to my advisors, Prof. Pushpendra Singh and Dr. Aman Parnami, whose guidance and mentorship have been pivotal throughout this journey. Their insights, encouragement, and steady support have left an indelible mark not only on this thesis but also on my academic and personal growth. Their mentorship shaped the direction and course of this research, nurtured my foundational research skills, and shaped me into the researcher and thinker I am today. While many moments along the way were challenging, I now look back with deep appreciation for the difficult questions they asked, questions that expanded my perspective, sharpened my approach, and pushed me to grow. I am truly grateful for their patience, nurturing my curiosity and independence, and supporting my academic freedom, ensuring I always had the resources and environment needed to pursue my work wholeheartedly.

I extend my sincere gratitude to my thesis committee members — Prof. Ponnurangam Kumaraguru, Dr. Rajiv Ratn Shah, Dr. Anmol Srivastava, and Dr. Charu Monga, who have supported and guided my work from its inception through every stage of this journey. Their invaluable insights and thought-provoking discussions have continually challenged

me and enriched the depth and direction of my research. I am deeply grateful for their time, encouragement, and unwavering belief in my work.

This dissertation and the larger journey of my research career would not have been possible without the guidance of three very important mentors who have shaped my academic path in profound ways: Prof. M. Balakrishnan, Prof. P.V.M. Rao, and Dr. Piyush Chanana. You were the ones who first introduced me to the world of research and helped me discover a deep and lasting passion for it, a passion that continues to shape my professional aspirations. Thank you for always being my champions, believing in me, and offering your wisdom and support whenever I needed it. All of your mentorship laid the foundation for everything that has followed and everything that is yet to come.

There are two more remarkable individuals without whom this journey would not have been possible. My father, who has been my constant pillar of strength and support — thank you for ensuring I never had to worry about anything beyond my research and for always encouraging me to stay focused on my PhD. Now that this phase is finally getting over, I hope I can shoulder the responsibilities I should have taken earlier, allowing you the freedom to relax. My husband, Pulkit, for living up to the role 'life partner' in the truest and fullest sense. I could never have envisioned this path for myself had it not been for your unwavering belief in me. You were the one who first pushed me to take the leap into a PhD, and that steady faith has been the thread running through every stage of this journey — from its very beginning to its end, and everything in between. Thank you for being my anchor through every storm and crashing wave that came my way, both in this journey and in life. I would not have been able to withstand any of them without you by my side. You have been my loudest cheerleader, fiercest critic, and unwavering refuge in moments of deep self-doubt. I often joke that the 3Ps in my life - Papa, Pulkit, and Dr. Parnami- were the ones who pushed me into the PhD boat. But as I stand now, nearly on the other side, I can also say with complete certainty that it was also the 3Ps - Papa, Pulkit, and Prof. Pushpendra, who pulled me through it. This journey would not have been possible without

your unwavering belief in me, your support, and your presence at every step. I cannot thank you all enough for introducing me to this path and walking beside me until the very end.

To my mother, thank you for shaping me into the firm and resilient woman I am today and instilling in me the courage and discipline that this journey demanded. Because of you, I learned what it means to persevere with grace and grit, and it is because of you that I could stay the course. Your prayers worked in ways I could never fully understand, guiding me, protecting me, and paving the way forward, even in the most challenging moments. I am deeply grateful to my sister, Lakshita, for wholeheartedly taking charge of the home front during the countless days when I was completely consumed in my work and had no capacity for anything else. She not only managed everything at home with ease but also doubled as my personal social media feed, keeping me updated on all the trends and new-generation buzz, making sure I didn't turn into a complete hermit during this journey. I cannot thank her enough for feeding me all the amazing food, her spot-on food recommendations, and for thoughtfully catering to all my stress-eating phases, support that truly kept me going when I needed it the most. I also extend my heartfelt thanks to my family-in-law for their steady support and understanding throughout this journey. I sincerely apologize for the crucial moments I've missed. Your patience, love, and encouragement have meant more than I can ever express.

Throughout this journey, I was fortunate to build a new family along the way in the form of my lab mates from both the Weave Lab and the Mélange Lab. Manideepa, Asra and Jasmeet, we shared the most significant parts of this journey, through its highs and lows, breakthroughs and breakdowns. I am endlessly grateful to have had you guys to share this journey with me, and I will always cherish the bond we built along the way. A special thanks to Asra for always being behind my back, checking in, and nudging me forward whenever I felt demotivated. To Sara and Kirti, your belief in me was often unspoken, humbling, and uplifting me when I struggled to believe in myself. More than anything, I hold your friendship closest to my heart. Shyama and Gautami, for all the incredible mo-

ments we shared, from countless rant sessions to food reviews, endless suggestions, and our ever-entertaining lab gossip. I deeply treasure the moments we all shared, the grievances we voiced together, the times we faltered, and the strength we found in lifting each other back up. You all turned even the hardest days into lighter ones, and for that, I will remain forever grateful. Anupriya, thank you for always asking the difficult questions and then also patiently helping me navigate through them. This list is very long — Pragya, Abhijeet, Vishal, Aryan, Kartik, Arpit, Dhruv, Sejal (and many names I may be forgetting) — thank you all for the laughter, the learning, and the unwavering support. I'm also thankful to Harshvardhan, Ayush, Yashika, Amolika, Rishabh, Arjun, Jayant, Khalid, Varnika, Raunaq, Akashdeep, and Ishbir for being part of exciting collaborations and for keeping me grounded, curious, and yes, even a little younger. I would like to put it this way — this is not a goodbye, just a heartfelt thank you, which is why *au revoir* (until we meet again), and not *bidding adieu*. I know, and hope, that our paths will cross again.

Last but by no means the least, I am also profoundly grateful to IIIT-Delhi for providing the resources, infrastructure, and a vibrant academic environment that made this journey possible. My sincere thanks to Jyoti, Binu, Priti Ma'am, Anshu Ma'am, Raju Sir, Sanjay Sir, Mohit, Sarika and all the administration staff for ensuring that everything beyond research was taken care of, allowing me to focus entirely on my work. I also thank the excellent hostel staff for making campus life welcoming and comfortable. A heartfelt thank you to the security guards and cleaning staff, whose daily efforts often go unnoticed but were essential in creating a safe, clean, and supportive environment throughout my time here.

As I stand near the end of this long and meaningful journey, I want to emphasize that it has been far from a solitary endeavour. I want to reiterate that this achievement is not mine alone; it is a reflection of the support, encouragement, and belief of so many of you who walked this path with me. I cannot thank you all enough for helping and supporting me navigate through this journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract

Virtual Reality (VR), with its immersive and interactive qualities, is increasingly recognized for its potential to transform education. Unlocking this transformative potential requires the principled design and sustainable adoption of Virtual Reality Learning Environments (VRLEs), ensuring they achieve their pedagogical goals and reach and empower diverse learners at scale. From a design perspective, there is a noticeable gap in the availability of principles, guidelines or frameworks tailored specifically for 3D immersive learning environments. Although the Human–Computer Interaction (HCI) literature offers a rich body of design principles for 2D multimedia learning environments, directly applying these to VR is impractical without thorough investigation, given the unique affordances. Beyond design-related gaps, current research on VRLEs also largely relies on ad hoc, one-off interventions, which underscores the need for systematic approaches that enable sustained adoption and integration into mainstream pedagogy.

Therefore, situated at the intersection of HCI, VR, and pedagogy, this dissertation advances the field by addressing the critical challenge of designing effective VRLEs while charting pathways for sustained adoption within mainstream education. Through a combination of empirical evaluations, an integration-focused study, and a comprehensive literature synthesis, this work provides evidence-based insights and frameworks that guide both the design and long-term incorporation of VR in education. As part of this work, empirical studies investigate two core design elements of VRLEs, verbal and spatial representations of learning content, to derive implications for effective design in immersive educational contexts. In parallel, it undertakes an exploration of students' perceptions, challenges, and barriers related to the sustained use of VRLEs aligned to their curriculum. The dissertation further incorporates a literature-based scoping exercise to identify key design parameters that influence learning effectiveness, in the form of a design space.

The findings demonstrate that VR design parameters meaningfully influence cognitive load and user experiences, and that the effectiveness of specific design choices varies across instructional contexts. In addition, by drawing on theoretical frameworks such as Self-Determination Theory, the dissertation outlines key considerations and best practices for integrating and sustaining VR into regular curricula. Furthermore, the identified design space, together with the empirical studies, illustrates how this space can be systematically leveraged to structure investigations that, in turn, inform the development of evidence-based design guidelines for VR learning environments.

Building on these insights, the dissertation therefore proposes a foundational framework to guide the development of design principles and practical recommendations for VRLEs. In doing so, the thesis aims to contribute to bridging the gap between theory and practice, enhancing learning experiences, and advancing the integration of immersive technologies in educational settings.

CHAPTER 1
INTRODUCTION

1.1 Research Context

Technological advancements over the years have played a crucial role in consistently transforming the education ecosystem [1, 2]. They have constantly reshaped teaching and learning practices by redefining how information and learning content are created, delivered, and consumed [3]. One such recent revolutionary shift in education has been the transition from two-dimensional (2D) to three-dimensional (3D) learning environments, driven by the rise of technologies such as Virtual Reality (VR) [4, 5, 6]. VR enables a range of experiences that were previously unattainable, particularly by simulating real-world scenarios that are otherwise inaccessible, hazardous, or impractical to reproduce in physical settings [6, 7, 8]. Its affordances, such as heightened immersion, an enhanced sense of presence, and increased interactivity, extend beyond the capabilities of traditional learning methods, thereby substantially enhancing its potential for application across diverse educational contexts [9]. Furthermore, while VR was traditionally employed in specialized training contexts such as aviation and medical simulations [10, 11, 12], the technology is increasingly democratized. It is transitioning from exclusive, high-cost setups like VR caves to more accessible, individual-use devices [5]. These diverse affordances of VR that hold the potential to enrich learning ecosystems, combined with its growing accessibility to broader audiences, underscore the need to investigate its role in everyday learning, moving beyond its initial use in specialized or less accessible contexts. This shift, however, necessitates rethinking and redesigning Virtual Reality Learning Environments (VRLEs) from the ground up, as the paradigm moves from elite settings to becoming a widely accessible educational tool.

However, research on developing effective and efficient VRLEs remains in its early stages. Instructional design decisions are often driven by practical, economic, or technological constraints rather than grounded in evidence-based research, resulting in VRLEs that are more technology-centered than learner-centered [13]. Unlike 2D multimedia learning environments, which are guided by well-established theoretical frameworks such as the Cognitive Theory of Multimedia Learning [14], the field of VRLEs lacks a comparable human-centered framework to inform their design. This absence limits the ability to evaluate and optimize design choices in VRLEs systematically and constrains their potential to support learning and pedagogy fully. Due to the lack of established guidelines and design frameworks, most current educational VR applications directly translate existing instructional materials, limiting their pedagogical effectiveness [15, 16]. This critical gap underscores the need for systematic inquiry into how VR's unique affordances can be leveraged to create effective and pedagogically grounded learning experiences. Moreover, much of the existing research and implementation of VRLEs remains confined to isolated, short-term interventions that primarily assess learning outcomes or user experience. These studies are often conducted in controlled laboratory settings rather than embedded within real curricular contexts. Consequently, our understanding of how VRLEs can be sustainably integrated into mainstream pedagogy remains limited, constraining their potential to deliver lasting educational impact. This calls for further investigation from an HCI perspective to enable their practical use, realize their full potential, and support their seamless integration into authentic educational settings [17].

1.2 Research Questions

Therefore, positioned at the intersection of Human-Computer Interaction (HCI), VR, and education, this dissertation aims to aid the design and adoption of VRLEs into mainstream pedagogy by answering the following broad research questions.

1. What design strategies grounded in pedagogical theory can guide the development

of VRLEs to improve learning effectiveness and user experience within educational contexts?

2. What factors influence the effective design of VRLEs, and how can this knowledge guide designers and researchers in identifying gaps, opportunities, and strategies for creating impactful learning experiences?

3. What factors shape students' sustained use of VR in learning, and what conditions support its long-term engagement and integration?

1.3 Contributions

Grounded in Human-Computer Interaction (HCI) research, this dissertation draws on a comprehensive literature review, empirical studies, and longitudinal research to make several key contributions to the field. Firstly, it advances the understanding of VRLEs by offering empirical insights into their effectual design. Building on the Cognitive Theory of Multimedia Learning, initially developed for 2D environments, this thesis reexamines established learning principles within the unique affordances of 3D immersive spaces and derives context-specific implications for design. In doing so, it advances the design landscape of VRLEs, setting a precedent for how foundational learning theories can be meaningfully extended to other VR affordances and diverse educational contexts. Secondly, this dissertation outlines best practices and key considerations for the sustained adoption of VRLEs within mainstream curricula. By providing theory-embedded insights into adoption and long-term integration within real-world educational contexts, it extends HCI research by moving beyond questions of usability and user experience toward sustained pedagogical integration. It advances VR scholarship by shifting the focus from short-term interventions and controlled laboratory studies to scalable, curriculum-embedded practices that confront real-world implementation challenges. For the learning sciences, it contributes actionable guidance on embedding immersive technologies into formal curricula, bridging

the gap between experimental research and practical, classroom-based adoption. Finally, this dissertation synthesizes a structured design space for VRLEs that equips researchers and practitioners with a comprehensive lens for understanding the VR design landscape, making informed design choices, and identifying critical gaps. By doing so, it establishes a foundational framework for the development of design principles and guidelines specific to VRLEs. For HCI, it extends the literature on design spaces and interaction frameworks into the emerging domain of immersive learning technologies, providing a human-centered lens for VR-based education. For VR research, it contributes a systematic approach to conceptualizing and organizing diverse affordances, enabling more rigorous design, evaluation, and comparison across studies. For the learning sciences, it offers a scaffold to align instructional goals with VR design features, bridging theory-driven pedagogy with practice-oriented technology design.

1.4 Authorship and Contribution Statement

In the chapters that follow, the first-person plural pronoun "we" is employed to describe the work presented. This choice reflects the inherently collaborative nature of the studies, where colleagues and co-authors contributed through discussions, feedback, and supportive roles. At the same time, it is important to clarify that the central responsibility for the work, including the ideation, conceptualization, study design, implementation, data collection, analysis, and interpretation of results, was undertaken primarily by me. Thus, while "we" acknowledge the collective effort that supported and enriched this research, the substantive body of work reported in this dissertation represents my own scholarly contribution.

1.5 Overview of the report structure

This dissertation is structured into chapters that systematically trace the research journey and its contributions. Chapter 2 provides a review of the background and related literature, identifying existing research gaps and articulating the motivation for this work. The chapter

then revisits the research questions in light of the identified gaps and presents an outline of the dissertation, offering a brief overview of the studies conducted as part of this thesis. Chapters 3 through 6 present the core studies conducted as part of the dissertation in detail, each addressing a key contribution toward the research objectives and questions. Finally, Chapter 7 synthesizes the overall contributions and discusses their implications for future research.

CHAPTER 2
BACKGROUND AND RELATED WORK

In this chapter, I outline the study context of this thesis and position my research at the intersection of HCI, VR, and learning and education.

2.1 Background: Virtual Reality in Education

VR has been proven to be a helpful medium in numerous pedagogical contexts, including but not limited to those that involve certain levels of risk, are logistically expensive, are not easily accessible, or require upscale visualizations [8]. It amplifies the real-world learning experiences by allowing the manipulation of objects and parameters in the learning environment and enhances the sense of physical, environmental and social presence [13].

With its interactive affordances and effective support for hands-on learning, VR has been positioned as an ideal medium for teaching procedural skills, establishing its traditional application in training aviation and medical skills like flying simulations and laparoscopy [10, 11, 12]. Over time, its applications have further expanded to training a variety of other procedural skills ranging from safety and security training [18, 19, 20], operating heavy machinery [21], and vocational skills like painting, plumbing and welding [22, 23, 24, 25].

However, with the advancements in technology, reduction in hardware costs and increasing popularity, the use of VR for teaching is further expanding beyond procedural skills to teaching factual and conceptual knowledge for STEM subjects, ranging from but not limited to biology [26, 27] , environmental science [28], astronomy [29] and computer science [30]. It is also being used in the context of novel learning techniques embedded in pedagogical theories like constructivism and constructionist theories like imaginative writing [31], museum exploration [32] and field trips [33]. VR is also being extensively used

for language and culture training [34, 35].

Therefore, as VR continues to expand as a medium for teaching, it becomes essential to prioritize effective design along with the sustained adoption of VRLEs. Achieving this requires moving beyond the simple transposition of instructional content across media and instead embracing a design-oriented approach grounded in robust pedagogical theories and principles that directly support learning goals. Equally important is the alignment of VRLEs with established curricular frameworks, which is critical for ensuring their long-term viability and successful integration into formal educational contexts.

2.2 Related Work

2.2.1 Design-Centered Learning Environments

2D multimedia learning environments

A vast corpus of literature exists on designing principles for 2D multimedia learning environments. A prominent work in this area, The Cognitive Theory of Multimedia Learning (CTML), discusses the existence of two main information processing channels of the learners: the visual channel, which processes images, videos, and animations and the verbal channel, which processes textual and narration components of a learning module [14]. This theory further lays the basis for various design principles targeting individual design components of multimedia learning environments.

The Multimedia Principle suggests that combining words and pictures enhances learning compared to using pictures alone [36]. The Coherence Principle advises reducing extraneous material in instructional design to focus on relevant content [37]. The Split Attention Principle emphasizes minimizing divided attention by integrating multiple information sources physically and temporally [38]. Similarly, the Contiguity Principle advocates for spatial and temporal alignment of verbal and visual content to improve learning [37]. Lastly, the Signaling Principle highlights the importance of cues in directing learners' at-

tention and organizing material [39].

A range of studies has examined these principles across varying contexts, thereby contributing to their refinement and standardization. For example, Tabbers et al. found multimodal instructions to be advantageous in system-paced animations, whereas visual-only instructions proved more effective in learner-paced settings, effectively demonstrating a reversal of the modality effect [40]. Similarly, Lee et al. highlighted the role of learner characteristics by showing that animated visual representations benefited individuals with low spatial ability more than those with high spatial ability [41]. Together, such findings, drawn from diverse experimental contexts, have culminated in the establishment of standardized design principles [37].

In addition, prior literature includes standalone investigations examining how specific design parameters in the presentation of learning content influence learning outcomes within 2D multimedia environments. For instance, instructions in the auditory modality have proven to give better results than textual instructions for learner performance [42]. Similarly, pictures and animations have been evaluated to have faster learning as well as execution times [43, 44] as compared to textual instructions. Moreno and Mayer introduced animated pedagogical agents in addition to textual and auditory content and found it to have no effect on learning performance [42]. The findings of these studies suggest that design principles intended to enhance the effectiveness of multimedia instruction are often context-specific and, as such, cannot be directly or uncritically transferred to other learning environments [45]. Therefore, the principles derived from experiments in 2D digital multimedia contexts cannot be seamlessly translated to 3D immersive environments like VRLEs. The unique affordances of VR, such as spatial interaction, embodiment, and presence, necessitate a re-evaluation of these design parameters, taking into account both established moderating factors and those specific to the immersive nature of VR.

3D immersive multimedia learning environments

Building on these limitations, recent research has begun to empirically investigate the effectiveness of design parameters within fully immersive 3D VR environments, acknowledging the unique affordances and challenges that distinguish them from traditional 2D settings. Researchers have explored various verbal content representation parameters for designing VR environments. Mayer extended their work in 2D multimedia learning environments to evaluate the effect of narration, text and a combination of both on the presence, retention and transfer of knowledge for HMD-based VR. They found learning with animation and narration or with animation, narration, and on-screen text is more efficient than learning with animation and on-screen text for both desktop and HMD environments [46]. The findings contradict prior studies on verbal redundancy in 2D multimedia learning, which claimed that adding redundant on-screen text to spoken explanations did not hurt or help students' learning [47, 48]. Baceviciute et al. compared textual vs audio learning content representations in VR to find reading superior to listening for learning outcomes of retention, self-efficacy, and extraneous attention [49]. Results show that participants in the redundancy condition performed equally well on retention and transfer post-tests. Baceviciute et al. further evaluated the redundancy principle in VR and found that redundant content was not more cognitively demanding than written content alone [50]. Liberman et al. evaluate the effectiveness and applicability of the modality principle for learning with low immersion VR to find no significant change in knowledge gain when learning with on-screen text compared to spoken narration but a higher cognitive load in case of narration [45]. Dingler et al. explored comfortable reading settings in VR by with a study focusing on parameters like text size, distance, convergence, angular size, view box dimensions, positioning, background colors, and font type [51]. Similarly, for representation of virtual characters in VR, there have been works discussing implications for the design of pedagogical agents in VR based on comparisons between the presence of a real instructor immersed with students in the environment vs. training with recordings of instructors [52,

53]. Petersen et al. discuss the effect of the appearance and behavior of pedagogical agents on knowledge gain [54].

There have also been explorations with respect to spatial representation of content in VR environments. Rzayev et al. investigated the placement of notifications in VR at four locations (Head-Up Display, On-Body, Floating, and In-Situ) for three types of VR environments: open, semi-open, and closed to understand their integration in VR without breaking immersion [55]. Hsieh et al. evaluated an individual's receptivity to message notifications during four VR activities (Loading, 360 Video, Treasure Hunt, Rhythm Game), using three types of displays (head-mounted, controller, and movable panel) [56]. Chua et al. evaluated the effect of 9 different display positions of a monocular OST-HMD (combination of 3 elevations (+12.5°, 0°, -12.5°) and 3 azimuth angles (-17.28°, 0°, +17.28°)) on performance (noticeability) and usability (distraction, comfort) for the user [57]. Rothe et al. compare static and dynamic subtitling in VR environments wherein the texts are fixed in front of the viewer and statically connected to the head movements for the static subtitles and are placed near the speaker in case of dynamic subtitling [58]. Similarly, for Smart Glasses, Rzayev et al. compared text presentation in the top-right, center, and bottom-center positions with Rapid Serial Visual Presentation (RSVP) and line-by-line scrolling for the Microsoft HoloLens [59]. Mathis et al. introduce the concepts of wall, below-screen, and egocentric messages to convey them to users during TV viewing experiences [60]. McNamara et al. used eye tracking as an attention indicator to identify objects of interest and reveal labels associated with these objects when the user attends to them [61]. Dominic et al. considered the effects of screen-fixed vs. world-fixed virtual annotations on performance during a navigation task in virtual reality [62].

While parameters such as modality and virtual character representation have been specifically investigated within educational settings, spatial representation — for example, the placement of labels and notifications — have been explored in more general VR contexts. Unlike textual and agent representation, where some work has been done around educa-

tional content, spatial representation research has been focused on the design of notifications, labels, and subtitles and not learning content. In contrast to these elements, which are sporadic and temporary in a simulation, learning content in VRLEs needs to be present for much larger durations. Additionally, learning content is required to be absorbed and comprehended, contrary to notifications which are just required to be detected and responded to at the moment. While notifications may be contextually completely different from the task at hand in a virtual environment, learning content is the core content of a VRLE. It has to be paid attention to and used at all times while in the environment, unlike these elements. Therefore, these results cannot be generalized for higher complexity stimuli like learning content.

Despite growing interest in the development of design-centered VR environments, several critical gaps remain unaddressed. First, explorations of design principles for various parameters are not consistently situated within educational contexts, limiting their relevance for learning-focused VR applications. Second, existing findings often lack of consensus in findings, largely due to evaluations being conducted with a narrow set of moderating factors. This restricts the potential to derive generalizable design recommendations or guidelines for VRLE design. These limitations highlight the need for a more comprehensive analysis of design principles for VR environments that (1) specifically targets educational use cases and (2) systematically incorporates a broader range of moderating factors. Addressing these gaps is essential for progressing toward a cohesive framework or theory for the effective design of VRLEs. This gap establishes the rationale for the next two chapters, which aim to advance understanding and provide empirical insights into how VRLEs can be more effectively designed and integrated.

Evaluative measures for design parameters

The proposed design principles are largely informed by studies that investigate how variations in design parameters influence learning outcomes. Common measures in this liter-

ature include knowledge gain, knowledge transfer, and cognitive load. While knowledge gain and transfer have generally been found comparable between VR and other learning media, outcomes such as presence, immersion, and particularly cognitive load tend to vary substantially depending on the learning context and design choices [63]. Given this variability, cognitive load emerges as a critical factor for understanding and optimizing the effectiveness of VRLEs. Therefore, although this thesis evaluates a broad spectrum of learning outcomes, its primary emphasis is placed on managing learners' cognitive load, as this dimension most directly shapes the usability, efficiency, and pedagogical value of VR-based instruction [64].

Cognitive load refers to the load experienced by subjects on the working memory when conducting various tasks [65]. According to the CTML [14], three major types of cognitive processing occur during multimedia instruction: intrinsic cognitive load caused by the complexity of the material for the learner, extrinsic or extraneous cognitive load caused by inefficient instructional design or distractions during learning and germane cognitive load caused by the learner's motivation to exert effort [66]. Owing to the finite processing capacity of the human brain, an extensive amount of extrinsic cognitive load can hamper the learning experience because of the limited remaining cognitive capacity to process intrinsic and germane cognitive load [13]. This can lead to improperly designed multimedia environments turning out to be hedonic rather than utilitarian [13]. Thus, devising immersive learning environments to enhance generative processing and reduce extraneous processing in order to increase learning are some of the important instructional design goals to be kept in mind while developing VRLEs. Harnessing the unique affordances of this medium to enhance the affective appeal of virtual environments, thereby increasing situational interest, can help in achieving these goals.

Over the years, various techniques have been used to measure cognitive load subjectively and objectively [67]. These techniques can be broadly categorized into four types of methods for cognitive load measurement [65]:

- subjective (self-report) measures like rating scales.
- performance measures, such as task completion time, speed or correctness, and errors.
- behavioural measures, such as text input events and mouse-click events.
- physiological measures, such as galvanic skin response, heart rate and EEG.

Throughout this work, we employ a combination of these methods and triangulate data from multiple sources to gain comprehensive insights into how various design parameters influence different types of cognitive load experienced by users in immersive learning environments.

2.2.2 Design Spaces in HCI: A Framework for Mapping Dimensions, Visualizing Coverage, and Identifying Gaps

A design space is a theoretical framework that describes the different possibilities for designing an artifact based on available technological alternatives, the domain of interest, and references from related existing artifacts [68]. A wide range of HCI literature has leveraged design spaces as structured frameworks to analyze and explore complex, multidimensional design problems. They have helped gauge the potential of existing technologies like input devices [69], smartphones [70] and upcoming technologies like 3D printable interactivity [71], eye gaze interaction [72], sketching interactions in VR [73] among others.

One of the earliest foundational contribution in HCI around design spaces is from Card et al., who systematized knowledge about input devices in the form of a design space [69]. Extending the exploration of input modalities, Arora et al. formulate a design space for jewellery-enabled input techniques, positioning jewelry as both a cultural artifact and a technological material for shaping wearable-based input [74]. Similarly, Ballagas et al. present a design space for 3D printable interactivity, analyzing prior literature to identify gaps and uncover new research and engineering opportunities in fabrication-based inter-

action design [71]. In intelligent and assistive technologies, Lee et al. propose a design space to examine and explore the multidimensional space of intelligent and interactive writing assistants [75]. Likewise, Liu et al. develop a design space for real-time knowledge support systems using LLMs [76]. Focusing on creative representation, Zheng et al. identify core components and dimensions of visual note-taking, offering design strategies for future digital inking tools such as recomposition and styling [77]. In collaborative and communication-centered environments, Eriksson et al. introduce CoCe, a design space for multi-display collaborative games, which articulates key considerations shaping co-located interaction [78]. Anjos et al. discuss the design space of volumetric representations of people in terms of manipulating scale, orientation, and the position of holograms to enable better eye contact with the avatars [79]. Mathew et al. contribute a spatial audio design space, mapping relationships between recording and rendering techniques to guide design and implementation of immersive auditory experiences [80]. Design spaces have also been used to structure the exploration of embodied, physical, and wearable interfaces. Bae et al. present a cross-disciplinary design space for data physicalization [81]. In a similar vein, Vidal et al. construct a design space for wearables in sports and fitness practices, aligning user goals with technological capabilities to surface trends and inform future directions [82]. In entertainment and expressive media, Kim et al. expand the design space for live-streaming, particularly in the context of VTubing, by introducing six new dimensions related to avatar creation and control [83]. Goncalves et al. introduce a design space for balancing mechanics in multiplayer gaming [84].

In the broader domain of mixed and extended reality, several works have proposed design spaces to map complex interaction paradigms. Lee et al. present a design space for transformations between 2D and 3D visualizations in MR environments, examining how input parameters and user interactions influence these transitions [85]. Danyluk et al. explore the design space of Worlds in Miniature (WiMs), generating new examples and identifying opportunities to guide future research [86]. Zhang et al. introduce the Intelli-Embodied

Design Space (IEDS), combining designers, augmented reality (AR), and generative AI to support industrial conceptual design [87]. Rajaram et al. examine privacy-driven adaptation techniques in AR, outlining a design space that helps developers balance usability and privacy [88]. He et al. propose a design space for tangible cubes in MR, focusing on interaction space, visualization space, scale, and multiplicity [89]. Yu et al. define a design space for motion feedforward and corrective feedback in XR motion guidance systems, highlighting interaction effects between the two [90]. Langlotz et al. offer a design space for vision augmentations using digital eyewear, enabling systematic exploration of human–computer integration for vision support [91]. Liu et al. encapsulate possibilities for visualization view management in immersive systems, proposing a design space that informs prototype development through combinations of spatial layouts and interaction techniques [92].

Complementary work has also mapped design spaces specifically for immersive VR across varied application contexts. This includes gaze interaction [72], 2D and 3D sketching [73], embodied dance experiences [93], virtual rotations [94], data visualization [85], and heart rate representation [95]. Related research at the intersection of VR and accessibility explores design spaces for accessible AR/VR manufacturing applications [96], non-visual word completion interfaces [97], accessible data visualizations [98], and non-visual audio representations [99].

Among the various approaches to constructing design spaces, morphological analysis is one of the most widely used [69, 100]. It has served as the primary method for systematically structuring and facilitating design spaces in much of the existing literature. The morphological analysis approach involves characterizing and positioning all parameters associated with a problem within a multidimensional matrix known as the Zwicky box and positioning possible solutions into that matrix [71]. This box helps identify relationships between the solutions or families of similar solutions. Following their work on the design space for input devices, Card et al. demonstrated a design space created using morpholog-

ical analysis to discover new interaction designs in the field of HCI [101].

Therefore, to guide the effective design of VRLEs from a broader vantage point, Chapter 6 adopts a morphological analysis approach to synthesize and examine a comprehensive design space for VRLEs. This design space systematically maps the key design parameters involved in VRLE development, offering a structured overview of existing combinations, uncovered gaps, and emerging opportunities in the field. By organizing possible design dimensions in a unified framework, it enables the identification of underexplored areas and supports the discovery of novel design directions. Ultimately, this design space serves as both a locus of control for VRLE representation and a foundational tool for informing design decisions and developing evidence-based guidelines for effective VRLE design.

2.2.3 Real-world Adoption of VRLEs

An equally critical dimension of VRLEs, alongside effective design and the attainment of pedagogical goals, is their integration into mainstream education; without such integration, the very purpose of developing VRLEs is undermined, as their potential remains unfulfilled regardless of design sophistication.

While research on VRLEs in education is growing, most existing studies have primarily focused on either comparing VR with traditional learning methods or evaluated its standalone impact on learning outcomes and user experience, primarily to assess its feasibility in educational settings. Moreover, these evaluations have largely been confined to non-contextual laboratory settings and are typically based on single-exposure use of VR applications.

There has also been some preliminary work focusing on stakeholders perspectives and behaviors around the integration of VR technology into regular curriculum. A few studies have looked into the perceptions of instructors towards integration of VR in higher education institutions [1, 3, 102]. Results highlight instructors' generally positive perceptions of VR as a pedagogical tool [1], emphasizing its potential to enhance student engagement

and provide unique learning experiences while also identifying key considerations such as curriculum integration, logistical challenges, low self-efficacy, and cost-related barriers to its effective and sustained adoption in education [3, 102]. Jin et al. encompass a broader view by investigating the perceptions and challenges of all major stakeholders while trying to integrate VR into classrooms. They identify inequity in access, lack of collaborative social experiences and the crucial role institutional management plays in deployment, management and content creation as major factors affecting the integration of VRs into regular classrooms [103]. However, these studies are largely based on stakeholders' existing general perceptions of VR, rather than insights drawn from its actual exposure in educational contexts. Recently, some works have focused on exploring the in situ integration of VR interventions within classroom environments to more comprehensively examine their role and impact in educational contexts. Hagge et al. evaluate the feasibility of long term integration of VR in a Geography course at a higher education institution wherein a few students who volunteered got exposure to VR modules while others would view the VR wearer's projected VR scene [104]. Southgate et al. explore integration of VR in low-income school settings and identify how students and teachers experience and engage with IVR in classrooms, and the opportunities, challenges, and ethical considerations of its use [105]. Mäkelä et al. examine the logistical and pedagogical opportunities and challenges of integrating VR across a 12-week term through dyadic student experiences [106].

Most prior work on VR in education has either focused on general stakeholder opinions, lacking grounding in actual, curriculum-aligned experiences or drawn from controlled usage settings. This has led to limited insights into authentic and contextual user engagement with VR in educational settings. Chapter 5 of this work builds on this gap by offering non-mandatory access to VR throughout a semester-long course. The work is situated outside formal evaluations, and without incentives or penalties, aiming to gather authentic student perceptions and behaviors. Such an approach provides grounded insights into how VR can be sustainably integrated into regular educational contexts. This work uses the Self

Determination Theory (SDT) to inform and enhance effective and sustained integration of VR into mainstream educational settings, which is a psychological macro-theory of human motivation, growth and well-being [107, 108, 109]. Given its extensive application at the intersection of SDT and VR across domains such as gaming [110, 111, 112, 113], tourism [114], therapy [115, 116], and rehabilitation [117], this thesis extends the application of SDT to the design of VR-based educational experiences, positioning it as a guiding framework to encourage their long-term adoption.

2.3 Dissertation Outline

Drawing on the gaps identified in the existing literature, we revisit the research questions posed by this work.

RQ1: What design strategies grounded in pedagogical theory can guide the development of VRLEs to improve learning effectiveness and user experience within educational contexts?

RQ2: What factors influence the effective design of VRLEs, and how can this knowledge guide designers and researchers in identifying gaps, opportunities, and strategies for creating impactful learning experiences?

RQ3: What factors shape students' sustained use of VR in learning, and what conditions support its long-term engagement and integration?

These research questions were investigated through four studies, a brief overview of which is presented below, highlighting the overarching research agenda, the specific investigations undertaken to address the stated research questions, and the resulting contributions.

Study 1: The first study presents an empirical analysis of one of VR's defining affordances—the use of three-dimensional (3D) space. Unlike traditional two-dimensional screens, VR enables content to be spatially distributed and navigated within an immersive environment. This capability fundamentally alters how learners perceive, interact with, and engage in the learning process [118]. Therefore, the placement of learning content

in a VRLE is one of the important design aspects designers must consider while creating them to enhance their noticeability and efficient processing. It becomes extremely critical to determine the placement of learning content while leveraging this affordance, keeping in mind to avoid overlooking, overlapping, or obstructing relevant information in the environment. This study investigates how different spatial representations: world-anchored, user-anchored, and object-anchored affect key learning outcomes, including knowledge gain, knowledge transfer, cognitive load, and user experience in VRLEs. These effects are measured using self-reported scales and follow-up performance assessments. Additionally, a follow-up study incorporating semi-structured interviews explores user preferences and perceptions of these spatial representations. This case study makes a primary contribution to addressing RQ1 while also providing substantive insights into RQ2, collectively informing design recommendations for optimizing the spatial presentation of content in VRLEs.

Study 2: The second empirical analysis evaluates the verbal representation of learning content in VRLEs. While significant work has been done in this area in the context of 2D multimedia environments [14, 119], it cannot be directly translated to VR owing to its additional affordances. For the work done in the context of 3D immersive environments, particular VR-specific affordances and moderating factors have not been considered. Fulfilling this gap, the study compares different modality-redundancy combinations: text only, audio only, text + audio with full redundancy, and text + audio with partial redundancy for different types of learning content and varying levels of participants' VR experience levels. It uses self-reported scales, semi-structured interviews, and physiological sensor data to evaluate their impact on cognitive load and user preferences. The findings make a substantial contribution to RQ1, while reinforcing this contribution through complementary insights into RQ2, specifically regarding modality and redundancy choices within VRLEs.

Study 3: During my research, I found that most existing studies evaluate VR in education

through short-term, isolated deployments often detached from the curriculum they intend to enhance. These implementations are typically positioned as one-off interventions rather than tools embedded within sustained pedagogical practices. To understand the long-term adoption and integration of VRLEs in educational settings in situ and practice, I conducted a semester-long study in an ongoing university course. The study examines the alignment of VR in existing curriculum, followed by semi-structured interviews to capture students' attitudes, perceptions, benefits, and challenges associated with curriculum-integrated VR modules. This work directly addresses RQ3 by employing Self-Determination Theory (SDT) as a framework to outline best practices and key considerations for fostering student motivation in VRLEs, thereby supporting the sustained adoption of VR in mainstream educational contexts.

Study 4: Throughout this research, I identified the need for a structured framework and clear design guidelines to enhance the effectiveness of VRLEs. Inspired by the concept of design spaces in HCI, I am currently synthesizing a design space highlighting the current landscape of design principles research in the context of VRLEs. The design space represents the key dimensions or parameters that must be considered when designing VRLEs, the various values these parameters can take, and the extent to which these values have been evaluated against one another. The work will further validate the synthesized design space's descriptive, generative and comparative capabilities by classifying existing VRLEs, identifying gaps in evaluating parameter combinations, and highlighting opportunities for new design possibilities. By addressing these gaps and enabling innovative design approaches, this work seeks to answer RQ2 at a broader level by establishing a foundational framework to guide the development of more effective and efficient VRLEs.

CHAPTER 3
INVESTIGATING SPATIAL REPRESENTATION OF LEARNING CONTENT IN VIRTUAL REALITY LEARNING ENVIRONMENTS

This chapter, and the one that follows, presents two case studies conducted to highlight gaps in the literature concerning the empirical evaluation of varying design aspects within Virtual Reality Learning Environments (VRLEs). These case studies also explore how the findings differ from established principles in other learning media and how various moderating factors influence these outcomes.

This chapter presents an empirical evaluation of spatial representations—an affordance of Virtual Reality (VR) that remains underexplored in educational contexts. While spatial placement is a fundamental feature of VR, its specific impact within VRLEs has received limited attention. Although prior research has examined spatial representations in other domains, their influence on learning outcomes has not been sufficiently studied. In this chapter, we investigate how the spatial arrangement of elements within VRLEs affects learners' knowledge acquisition, cognitive load, and overall experience.

3.1 Motivation

VR provides a variety of unique affordances (like multi-modal interactions, haptic feedback, and 3D spatial representational capacity) [16] and constraints over 2D digital learning environments for designers to consider [120]. Spatial Representation is one of these unique affordances since content placement in VR can be distributed throughout the 3D virtual space instead of being limited to a 2D screen surface [118]. The placement of learning content within a VRLE is a critical design consideration, as it directly influences the noticeability of components and the efficient processing of information. Effectively leveraging this spatial affordance requires careful attention to avoid issues such as overlooking, over-

lapping, or obstructing important content within the environment. [61]. While researchers have evaluated the placement and modality of notifications [120, 55, 56], labels, and subtitles [118, 61, 57, 58, 59, 60] in VR to enhance integration and noticeability, the placement of learning content has not been investigated specifically [118]. To fulfill this research gap, we inform the spatial representation of learning content in VRLEs in this research work, with respect to four different placements in the VR environment: World-anchored, User-anchored (anchored to either controllers or the head-mounted display(HMD)) and Object-anchored. We have identified these four placements based on the affordances offered by VR and placements evaluated in previous research for other types of content [55, 56, 61].

We conducted mixed-methods research comprising a two-phase study. The first study is a between-subjects (n=42) experiment examining the effect of these four different placements of learning content in VR environments on various cognitive and affective measures [17] like learner's knowledge gain, transfer, cognitive workload, and user experience. They were evaluated using quantitative measures like knowledge-based tests, cognitive load tests like NASA TLX, and the UEQ user experience test. The follow-up study involves a within-subject (n=22) approach where users' preferences, likes, and dislikes across the four different kinds of information displays are gathered with the means of qualitative semi-structured interviews.

We investigate three main research questions in the following research work:

- RQ1: What are the effects of different placements of learning content in VR learning environments on knowledge gain, knowledge transfer, cognitive load, and user experience?
- RQ2: What are the user preferences, likes, and dislikes across various placements of learning content in VRLEs, and what factors affect these preferences?
- RQ3: Which display placements are more suited to present learning content across VRLEs?

3.2 Research Methodology & Findings

We conducted two experiments to investigate the effect of different spatial representations of learning content in educational VR systems. The first study evaluated the effect of four different placements of learning content in VRLEs on various learning and experience metrics. The follow-up study analyzed user preferences around these content placements. Both studies were approved by our University's Institutional Review Board, providing participants anonymity and receiving their prior informed consent and voluntary participation. Participants were compensated for their time with Amazon vouchers.

3.2.1 Experiment 1- Spatial Representation Effect Study

Study Design

To investigate the first research question, we employed a between-subject design with four experimental conditions wherein participants were exposed to the same learning material but with different placements of the learning content in the VR environment. The conditions represented the three types of spatial representations, comprising of four different placements in the VRLE: World-anchored, in which the learning content is displayed on a TV screen whose position is fixed in the virtual environment; user-anchored, in which the learning content is displayed on a panel anchored to the hand controllers in one condition and the HMD in the other condition and Object-anchored wherein the learning content is displayed on a panel that is anchored to the object of interest (to which the instruction is associated) and changes position with respect to that. The order of assignment was randomized by assigning each participant a unique ID and experimental condition prior to the study. Demographics, prior knowledge about the topic being taught, and prior experience with VR simulations were assessed in the pre-test survey. The post-test conducted immediately after the experiment assessed learning outcome variables, cognitive load, and user experience measures.

Procedure

Participants signed up for our study through an invitation mail shared across University mailing lists. Upon giving informed consent for participation, they had to take a pre-session survey to collect demographics and prior experience with VR and the topic being tutored. The participants were then immersed in the virtual environment.

After exiting the VR simulation, the participants were inquired about any discomfort, finally followed by the post-task survey. The post-task survey included a knowledge gain test, a knowledge transfer test (which was conducted later in the Design and Innovation lab of our institute to be performed on the actual machine), followed by questionnaires evaluating cognitive load measures and user experience. Finally, the participants were enquired about their availability and willingness to participate in the follow-up experiment.

The VR Learning Application

We developed a VR simulation in Unity 2020.3.26f1 for the Oculus Quest 2 VR system. The application was designed to facilitate learning about the laser cutting process for lab prototyping. We developed four versions of this application with identical environment design and instructions varying only in the placement of learning content in each version: (1) on a TV screen positioned at a fixed place in the environment, (2) on a panel anchored to user's hand controllers and the panel movement anchored to the user's controller movement, (3) on a panel anchored to user's HMD that moves around in the environment along with the user's head movement and (4) on a panel anchored to the object with which the instruction is associated. The world-anchored placement was designed similar to a classroom scenario where learning content is provided by teachers on a board placed in front of the students. Since students could move around in this learning environment, we fixed the initial placement of the board right beside the laser cutting machine such that it remained in front of the students during most of the tasks. Inspired by previous works on notification design [120, 56, 55], the controller-anchored placement was designed like a smartwatch.

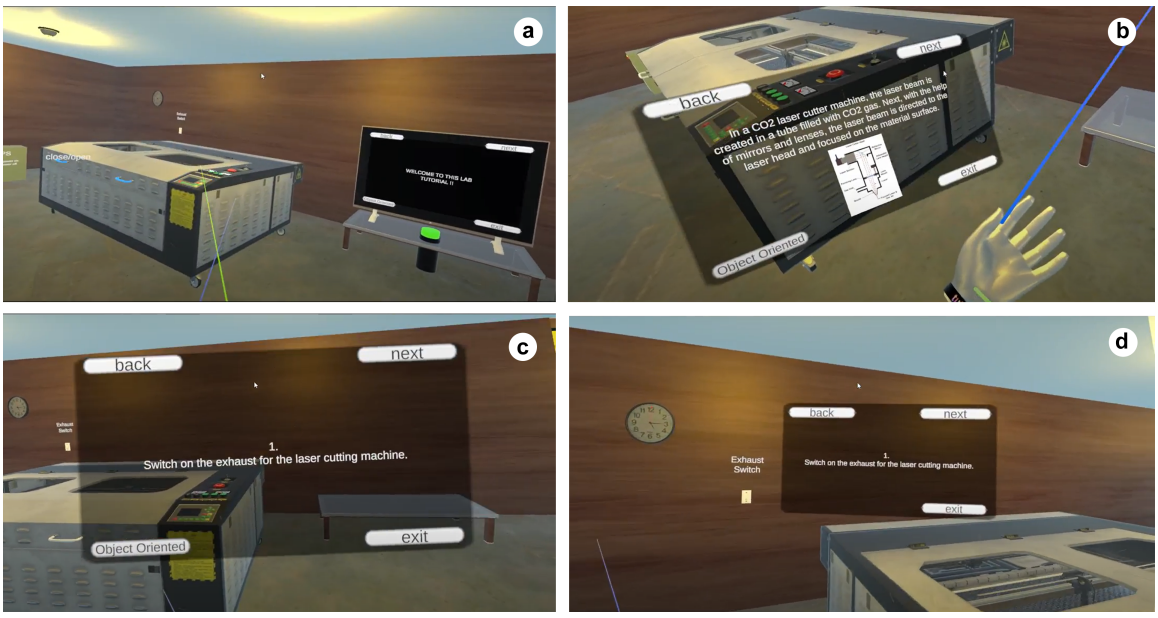


Figure 3.1: Four Spatial Representations for placement of learning content in VRLEs. (a) World-anchored: on a TV screen fixed in the environment. (b) User-anchored (Controllers): on a panel anchored to the VR controllers. (c) User-anchored (HMD): on a panel anchored to the head-mounted display. (d) Object-anchored: on a panel anchored to the object associated with current instruction.

However, since the amount of content we had to display was much more than a notification, we leveraged the spatial affordance by VR and displayed the panel mid-air while keeping it anchored to the users' wrists via controller tracking. The HMD-anchored placement was also motivated by earlier works [56, 55]. The panel was placed 1.25m away from the front of the VR headset, with its center coinciding with the center of the users' field of view. Using McNamara et al.'s [61] work discussing the relationship between object labels and user attention, we designed our object-anchored placement to draw the users' attention to the next area of interest wrt the learning content. The tutorial screenshots can be seen in Figure 3.1

We curated the learning content with the help of our institute's Design and Innovation (DI) Lab engineer, who is the key person responsible for training students on the laser cutting machine. Information was delivered to participants in English. The simulation highlighted a brief introduction to the process of laser cutting and its underlying principles, followed by virtually working through the procedure of using a laser cutting machine in the

lab. The simulation started with a brief tutorial about VR controls and actions (like moving in the environment using joysticks, teleportation, etc.) that would be required within the tutorial. This was provided in both audio and textual information displays. The content in the pre-tutorial was system paced, where the system moved to the next instruction only when the user tried out the previous instruction. Post the VR tutorial, the users could enter the main lab within the VR simulation, where they were first introduced to the concept of laser cutting, followed by a step-by-step tutorial to operate the laser cutting machine. The instructions were only displayed in the textual modality in order to ensure that users completely consume them from their placement in the environment and not in any other way. Additionally, this was learner-paced, and participants could move forward and backward in the tutorial at their own pace and as many times as they wished.

Participants

A total of 42 (27 male; 15 female) English-speaking participants were recruited for the study with an average age of 24.01 (sd=4.65). Table 3.1 shows the participant demographics. 2 of them failed to complete the experiment due to simulator sickness. The participants had a mean self-reported experience with VR of 1.88 (from 1= Not at all experienced to 5 = Extremely experienced). Mean familiarity with the topic of laser cutting was 2.2 (from 1= Not at all familiar to 5 = Extremely familiar). The median value was 2 for both of these parameters. 25 of these participants participated in the transfer test on the real-world machine.

Table 3.1: Participant Demographics Table

Age	Gender	No. of Participants	Gender	No. of Participants
18-24	M	19	F	8
25-34	M	8	F	6
35-44	M	0	F	1

Measurements

Learning Assessment: Participants' learning outcomes were evaluated with the help of two custom-designed tests. The knowledge gain test consisted of 8 multiple-choice questions (2 based on factual content, 2 on conceptual content, and 4 on procedural content from the tutorial). Its goal was to measure how much knowledge did the participants gain from the content presented in the tutorial (e.g., Content Text: Next, with the help of mirrors and lenses, the laser beam is directed to the laser head and focused on the material surface. | Question: In the laser beam machining process, the lens is used to? | Multiple Choice: (A) Deflect laser beams (B) Diverge laser beams (C) Converge laser beams (D) None of the above). The answer to each question scored 1 point for the participant.

The transfer test was to evaluate the transfer of learning from the virtual environment into the real environment. For this evaluation, the participants were asked to perform the procedure learned in the virtual environment in the real world on the laser cutting machine in our University lab. It was made sure that the 3D model used in the tutorial was similar to the machine in the lab to avoid any effect on the test. The transfer test was supervised by the primary researcher and our university's DI lab engineer, who also acted as the overall evaluator for the procedure. A transfer score was calculated for each student who performed the test based on the number of instructions they recalled from the tutorial (1 point for each step remembered).

Self Reported Cognitive Load: We used three self-reporting measures to assess participants' workload during the experiment. The first measure was composed of four individual items used to evaluate cognitive load: overall mental effort invested during learning measured using a measure from Paas (1992) [121], intrinsic cognitive load using a measure from Ayres (2006) [122], extraneous cognitive load using a measure from Cierniak et al. [123] and perceived concentration during learning using a measure from Salomon [124]. All items were reported on a 9-point Likert scale. A 10-item cognitive load instrument dis-

cussed by Leppink et al. [125] to measure intrinsic, extrinsic, and germane cognitive load was also used to consolidate findings. Finally, to triangulate our findings, we also used the NASA TLX [126] test to assess the workload experienced by participants while experiencing the virtual environment in all four conditions.

User Experience: The UEQ (User Experience Questionnaire) [127] was used to measure the participant's overall user experience with the application. Its 26 questions investigate 3 aspects of experience across 6 scales: Attractiveness, Pragmatic quality (Perspicuity, Efficiency, Dependability), and Hedonic quality (Stimulation, Novelty).

Findings

Since our experiment had one independent variable (placement) with four types (factors =1, levels>2), we applied parametric analyses using one-way ANOVAs, non-parametric analyses using the Kruskal-Wallis test, and used subsequent post-hoc independent sample t-tests and Wilcox tests, where applicable using the RStudio tool [128]. A summary of the findings for all the measures can be found in Figure 3.2.

Learning Assessment: We employed two learning-outcome measures - Knowledge Gain and Knowledge Transfer. Parametric analyses using one-way ANOVAs were applied. Fig. Figure 3.2 (a) and (b) show the box plot for knowledge gain and knowledge transfer with mean values and variance. Although we did not find a significant difference in the knowledge gain values, the mean knowledge gain was found to be the highest for the object-anchored placement condition (mean = 6.4(out of 8) and sd= 1.5) and lowest for the HMD anchored placement (mean = 5.1 and sd = 1.28).

For the knowledge transfer test, the highest average student score was found for the HMD placement condition (mean = 16.40000 and sd = 2.408319), and the lowest average scores were found for the TV screen placement condition (mean = 13.66667 and sd =

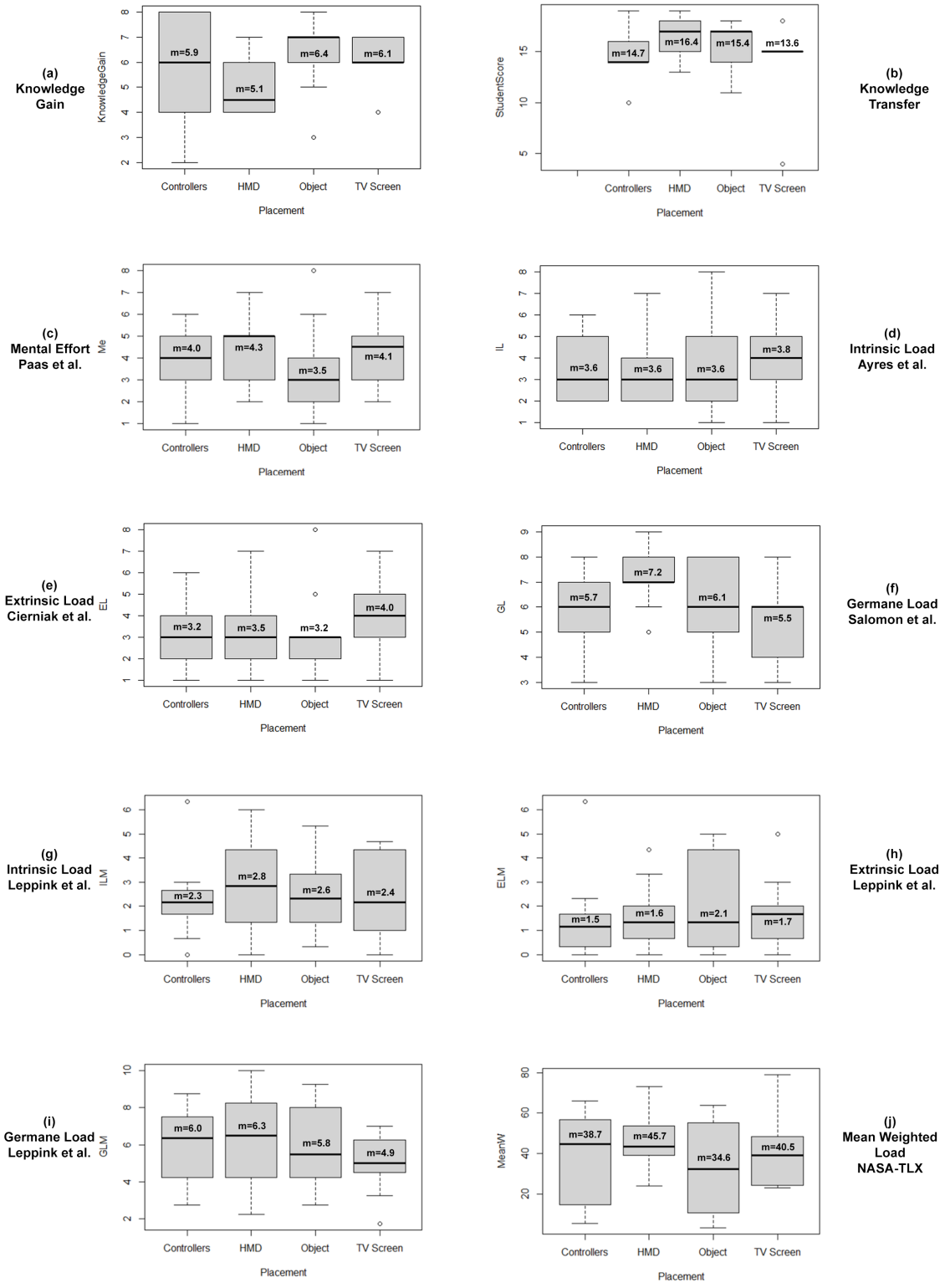


Figure 3.2: Box plots for Learning Outcomes and Cognitive Load Findings (the horizontal black line denotes Median and 'm' denotes mean values)

4.885352). The object-anchored placement condition resulted in the second-highest transfer scores (mean = 15.42 and sd= 2.51). However, on conducting the Kruskal-Wallis test, the knowledge gain test scores for all four placement conditions were found to be statistically insignificant (p-value = 0.67).

We further conducted qualitative interviews with participants post the transfer test to gauge their experience of learning in VR and then performing the task in the real world. Users were enquired about the overall usefulness of learning in VR and aspects of learning in VR that they found useful and not so useful. All participants except for one found learning in VR to be helpful. *"If you do it in the real world, somebody tells you what to do, then one can learn faster"* (M18). Some of the aspects of learning in VR mentioned to be helpful by the participants were: increase in confidence to perform in the real world post learning in VR, reduced risk of making mistakes with real-world equipment, similarity to the real-world learning experience, reduced dependence on instructors, the possibility of going over the learning content multiple times, interactivity and experientiality. These are in congruence with the advantages of VR discussed in previous literature extensively.

Less tangibility compared to the real world, the requirement of immense practice to get comfortable with VR, and the bulkiness of the headset in case of long simulations were some of the things they did not like about learning in VR.

Self Reported Cognitive Load: The four single cognitive load items from Paas, Ayres, Ciernak, and Salomon [121, 122, 123, 124] were analyzed using the parametric one-way ANOVA tests. Fig. Figure 3.2 (c),(d),(e), and (f) show the box plots for all of them. The box plot shows higher mental effort for HMD and TV screen conditions. The intrinsic load can be seen to be almost similar for all conditions (which was expected to be considering learning content was exactly the same in all four conditions and intrinsic load owes to the content) with a little higher value for the TV screen condition. The plot representing extrinsic load shows similar values for the Controllers, HMD, and object-anchored conditions

but a higher value for the TV screen condition which can also be confirmed from our findings of the follow-up study (discussed in findings of Study 2). The germane cognitive load was found to be the highest for the HMD condition with similar values for the other three conditions. However, no statistically significant differences were found for any of these loads from the one-way ANOVA calculations.

The 10 question-based cognitive load from Leppink et.al [125] were analyzed for intrinsic(Q 1,2,3), extrinsic(Q 4,5,6) and germane(Q 7,8,9,10) load using the parametric one way ANOVA and asymptomatic Kruskal-Wallis test based on the fulfillment of the conditions for parametric data. The box plots for the three types of cognitive load for all four placements can be seen in Figure 3.2 (g), (h), and (i). The intrinsic cognitive load plot shows similar values for the four placements, which should have been the case since all four conditions provided the exact same learning content. For the questions pertaining to extrinsic cognitive load, similar values were found. The ANOVA and Kruskal Wallis tests also showed no significant differences among these values.

For the NASA TLX questionnaire, we analyzed both raw and weighted scores based on: the factors representing the most important contribution to workload in 15 pairwise comparisons of 6 factors: physical demands, mental demands, temporal demands, performance, effort, and frustration, and magnitude ratings on the scale of 0 to 100 representing these factors. The Mean Weighted Workload was found to be the highest for the HMD placement (mean=45.70000 sd=14.94967) and the lowest for the object-anchored placement (m=34.58095 sd=23.12590). However, parametric one-way ANOVA showed the differences to be statistically insignificant.

User Experience: The average results for the six UEQ scales for all four placements across 40 participants can be seen in Figure 3.3. Based on the UEQ results across the 40 participants, it can be seen that overall the object-anchored placement provided the best user experience. While it scored the highest on the attractiveness, perspicuity, and novelty scale,

its scores on the remaining scales were also close to the highest. The TV screen placement, on the other hand, scored the lowest on all the scales except the novelty one, where it scored the second lowest. Pairwise t-tests on all the scales across the four placements showed significant differences between TV screen vs. HMD placement (p=0.021) and TV screen vs. object-anchored placement (p=0.042) on the Stimulation aspect. Significant differences were also found between the TV screen and the object-anchored placement on the attractiveness aspect (p-value = 0.021). On the novelty scale, the object-anchored placement score was significantly higher than the HMD-anchored placement (p-value = 0.005).

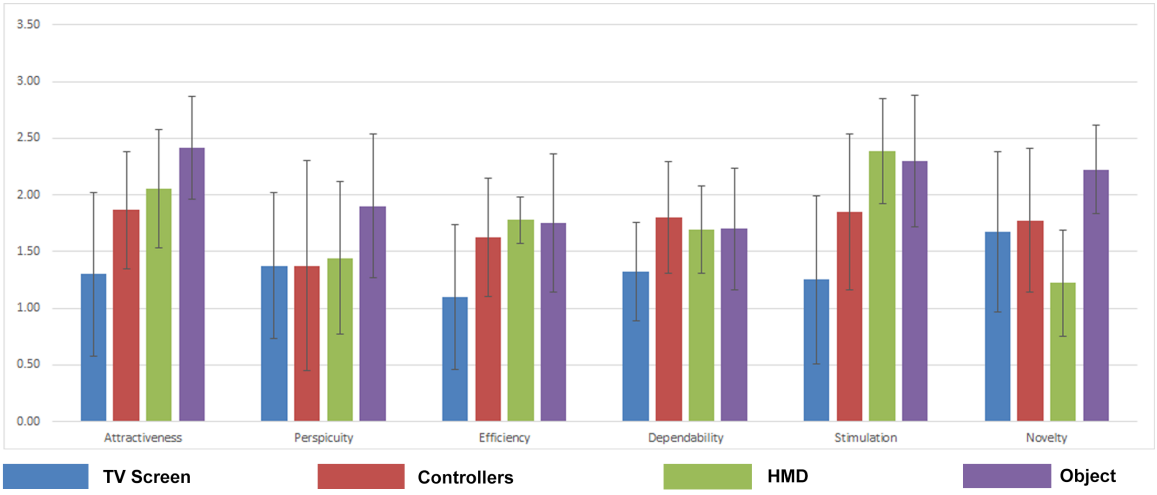


Figure 3.3: User Experience Scale-Means for the four placements of learning content

3.2.2 Experiment 2 - User Preferences Study

Study Design

To investigate our second research question, a within-subject approach was employed with a single experimental condition. In this study, the participants went through a similar virtual simulation as used in Experiment 1, but with all four learning content placement options available. It was up to the users to choose the placement of learning content they preferred. The placement could be changed anytime and any number of times during the experiment. A semi-structured interview followed the experiment to assess user preferences across the

various learning content placement, understand their likes and dislikes, and the rationale behind their choices.

Procedure

Participants who had volunteered from the previous study to be a part of the follow-up study were contacted to schedule participation in this study. After taking the informed consent and demographics survey, the participants were immersed in the same virtual learning environment as in the previous experiment but with some additional instructions and features associated with changing the placement of learning content in the VRLE. Simulation logs and screen recordings were also collected during the experiment to assess user behaviors as to when and where in the experiment they changed these placements. The post-session after the experiment included a semi-structured interview to understand and assess the choices users made regarding the placement of instructions while undergoing the simulation.

The VR Learning Application

A single VR simulation was developed for this experiment in Unity 2020.3.26f to run on the Oculus Quest 2 VR system. The application similar to the one used in the previous experiment facilitated learning about the laser cutting process through a brief introduction to the process of laser cutting, some key concepts associated with the topic, followed by procedural steps to use a laser cutting machine in the lab. The learning content in the simulation was displayed on a TV screen placed beside the laser-cutting machine model by default. The participant however could choose to drag this TV screen anywhere in the environment (unlike Experiment 1) or choose to place the learning content in either of the remaining three conditions: on a panel anchored to their left or right wrist, on a panel anchored to their HMD or on a panel anchored to the object in the virtual environment associated with the instruction.

The simulation comprised a pre-tutorial to train participants for changing the placement

of learning content during the experiment followed by the actual lab tutorial. The learning content was the same as that used in the previous experiment as the purpose of this study was to only understand user preferences and rationales around their choice of placement. Similar to the previous study the pre-tutorial instructions were system paced and provided to users in a text + audio format while the instructions related to the laser cutting machine were learner paced and provided only in textual format.

Participants

From the participants who consented to be a part of the follow-up study, a total of 22 (14 male; 8 female) participants were recruited for the study with an average age of 24.54 (sd=5.21).

Data Collection

Screen Recording and Simulation Logs: While performing the experiment, we recorded the user VR sessions to log the choice of placement of learning content of users and changes in the placement during the course of the experiment if any. To facilitate these screen recordings, the application was streamed on the Oculus headset via Unity using the airlink option provided by the Oculus app on the Windows system. Apart from this, our system also collected textual logs whenever a participant changed the placement of instruction during the experiment. This data helped us in verifying and interact with our participants during the follow-up semi-structured interviews. Additionally, it also helped in identifying patterns in relation to user preferences around the presentation of learning content in different placements for learning-related simulations in VR.

Semi-structured Interviews: Finally, at the end of the simulation, we conducted an open-ended semi-structured interview where we discussed with participants about their choice of placement of learning content in the VR, whether they preferred changing these place-

ments during the experiment, and the rationales behind changing these placements at that particular instance of the experiment if they did so. The interview was done right after the participant underwent the simulation experience.

Findings

We collected textual and video logs and interviewed each participant at the end of this study to determine user preferences, if any, around the spatial representation of learning content in VRLEs. All interviews were audio recorded for post-analysis. They were transcribed and analyzed by the first author using thematic analysis. The final results for user preference for the spatial representation were triangulated by analyzing the textual and video logs collected while the user was performing the experiment as well as the interview data.

The instruction panel anchored to the controllers was clearly the most preferred choice (preferred by 9 out of 22 participants) for the placement of instructions. This was followed by the instruction panel anchored to the object of interest (preferred by 6 out of 22 participants). One participant rated both spatial representations equally. Three participants whose first preference was the controller-anchored panel reported the object-anchored panel to be a close second preference. This was followed by the panel anchored to HMD preferred by 3 participants and instructions on a TV screen which was preferred by 2 participants. Interviews suggested that 4 participants found the HMD-anchored panel to be really comfortable for instructions that were just to be read and required performing no action. 13 participants clearly mentioned the TV screen placement to be the least preferable. One participant could not pinpoint a preferred representation and felt improvements required by all the placements offered within the experiment.

Likes and Dislikes regarding Spatial Representations

World-anchored: The learning content display on the TV screen was considered the least preferred in comparison to the other three representations by most of the participants. Max-

imum negative comments about this placement revolved around the need to perform an additional task to either move the TV along with them or come back to the TV screen after performing every instruction to view the next instruction. M21 mentioned: *"in case of the TV screen we have to go to the TV screen and come back again and then go back again and come back"*. M13 stated: *"I did not find the TV one to be useful because I have to drag it with me."* Participants mentioned this additional task to be hindering focus while learning: *"I can focus more on what I am doing while using the wrist one. I do not have to move to the TV again and again."* (M20). This additional task seemed particularly more hectic when the users had to perform the procedural instructions to operate the machine in comparison to when they were presented with factual and conceptual content associated with the laser cutting machine. *"I did use the TV one but to just move from here to there, I had to hold it, take it to another position, it was good when you are just reading through, but when you are doing instructions while reading on the TV that's not very good."* (M11). The other three placements were found to be mobile, and easier to read and use in comparison to this placement. M12, while talking about the object-anchored placement suggested: *"It is good because we are able to understand what is written over there and we don't have to really look or go to that TV screen every time for even a reading out some small information."* M15 also found object-anchored to be more advantageous as compared to this placement, stating: *"And if I have to move the TV around, in that case, object-oriented is better than the TV, it is similar, it is as large as the TV but it also has the benefit that it pops out where you have to do the work"*. M4 claimed the HMD anchored panel to be more convenient: *"For TV, I had to move. I would say HMD was better in terms of distance and readability"*. The users also had to maintain an optimum distance from the screen to ensure readability. M8 pointed: *"While I was using the television to use my instructions, I thought that I had to move a lot of times closer to the television or sometimes away from it so that I could read it properly."* Some users further characterized the TV placement to be very elementary: *"The point is if you are going to read it like this (from TV screen) why not just read it from a*

normal book" (M14).

However, some positives that the participants mentioned for this placement of instructions were the large size of the display panel and its stability: *"When I was looking at the diagram (on the wrist panel), the diagram was very small, it was difficult to read the text. When I saw it on the TV, it was better"* (M13). *"I used that only, the screen that was stationary because it was easier to see"* (M16).

User-anchored

Instruction panel anchored to controllers: Presenting learning content on the panel anchored to the controllers was considered one of the most intuitive ways of presenting instructions by the majority of the participants. The participants found it to be the easiest to use, M3 said: *"For the wrist one, it was so easy, you just have to click on your wristband and it just appears. It was more easy to see"*. M7 mentioned: *"when I wanted to see the instruction, it was easier for me to just switch it up and look at the instructions."* M10 also chose the wrist anchored content placement stating: *"I can move my hand away, do the task, and then bring my hand back, so it was easier to maneuver the next instruction."* Users also found looking at the learning content on a panel attached to their controller (wrist in the virtual world) to be very natural because of its similarity with the usage of a wristwatch. According to M21: *"I have the habit of looking at the watch often so it felt natural."* M22 pointed: *"I am a watch person, I like wearing a watch so it was easier for me."* Another advantage that the users found in this placement were the mobility it offered. M7 stated this particular placement *"like a portable instruction manual." M10 also indicated "it's always with you. So it's a little more mobile."* Finally, participants also claimed this placement to be non-obstructive in comparison to the other placements. M22 explained: *"the screen was so little that it did not distract me or didn't hide any message which was at the back or hide the environment which is beyond that small screen."*

Few participants, however, suggested experimenting with the size of the text and panel,

and the angle at which this panel is attached to the wrist could help make this spatial representation even more optimum and three participants reported fatigue while using this.

Instruction Panel anchored to Head-mounted Display: Although many participants found the content presented at this placement very convenient to read, its most negative aspect was that users found it obstructive. M1 explained: *"overhead mode was very easy to read, I really liked it, the only problem was that it was interfering with whatever I was doing." "Even after I know the instruction it still remains in front of me, but for the wrist one, once I understand the instruction I can lower my hand and the instruction goes away. And then when I want to access it, I can see it again."*(M6). There were other participants who found this representation to be solely obstructive and therefore disliked it completely. For M13, *"the head one was the most annoying because it was moving with my field of view."* M20 stated: *"the HMD one was blocking my view so I did not like it."* However, a few participants found the presentation of content on a panel anchored to the HMD as most readable. M1 mentioned: *"In HMD, the distance was very accurate."* For M4 also, *"HMD was more convenient since it was closer to me, I would say HMD was better in terms of distance and readability."* M8 also pointed out that *"the instructions were very readily visible. It was right there in front of me."* for the HMD-based display.

Object-anchored: The object-anchored placement of instructions was found to be the second most preferable spatial representation and was described to be orienting by the participants. M15 described: *"I think object-oriented one was great in the aspect that it popped out where we had to do the work..."*. *"The fourth one would be very comfortable because, for example, some people do not know what a UPS is, so suddenly when instruction pops up there they understand that this is UPS and go there."* (M5). However, the only issue that participants felt with this placement was the sudden shift in its position after every instruction. *"The only problem in that mode is that you have to search the screen whenever it*

changes position, you don't know where it goes and you have to roam around." (M1). *"So you're just like looking around, trying to see where the screen went, so the sudden change was kind of disorienting. I think the screen moving there kind of gives you a prompt that you have to move there. But the moving itself is not shown. It just vanishes from where it is. Unless, you know, these are the exact steps that you need to follow, you wouldn't have probably seen the screen and would have been just searching around looking for the screen."*(M11). However, some participants themselves suggested that an indication of the movement of the content panel would improve the preference for this spatial representation. *"So something, maybe the arrow mark while disappearing the screen showing that you should see this side... where is the next position should also be included in it."* (M5). M11 had a similar suggestion stating: *"If it would have taken me along with that thing (content panel), it would have been really helpful..."* M19 also suggested: *"in the object-oriented part, I think if there would have been an arrow kind of thing and you don't have to turn around the entire 360 degrees to find it out, that would have helped."*

3.3 Discussion

In the current study, we set out to explore the effect of various spatial representations of learning content in VRLEs. We discuss our findings with respect to our three research questions along with other learnings gained from the two experiments.

With regard to RQ1:*" What are the effects of these different placements of learning content in VR learning environments on knowledge gain, knowledge transfer, cognitive load, and user experience?"*, results showed that all four placements of learning content were similar in terms of knowledge gain and knowledge transfer.

Results also suggested that none of the placements was perceived to be more cognitively demanding than the others (significantly). However, while statistically significant differences were not reported for the sample that we evaluated, we observed some patterns by triangulating data from the results of the three cognitive load instruments used: the

single-item tests[121, 122, 123, 124], the validated Leppink et al. instrument [125] and the NASA TLX load index [126]. Similar mean values for intrinsic cognitive load were found for all four placements. Since intrinsic load is exerted by the learning content, this similarity was also expected since all four conditions had the same learning material presented to the participants. The controller-anchored placement was found to exhibit lesser extrinsic cognitive load (load attributed to instructional design) as compared to both the TV screen and HMD placements. Object-anchored and controller-anchored placements were ranked better in terms of mental effort /workload as reported by both the single-item test and NASA TLX. This is in coherence with our findings from the user experience test results and insights gathered from the second experiment where TV screen and HMD placements ranked lower in general. The germane cognitive load (motivation to exert effort) was found to be the best for HMD placement and the worst in the case of TV screen placement. This concurs with findings from our second experiment wherein users indicated the HMD placement to be very easy to use and the overall lack of liking across both experiments for the TV screen placement.

Statistically significant higher ratings were obtained for the object-anchored placement on user experience scales of attractiveness (Overall impression of the product), stimulation (excitement or motivation to use the product), and novelty(creativity of product design) in the first experiment. These are in agreement with findings from the second experiment wherein this placement was ranked to be the second most preferred placement.

In response to RQ2: *"What are the user preferences around various placements of learning content in VRLEs and what factors affect these preferences?"*, there was a clear inclination toward the wrist (controller)-anchored placement. This is analogous to results obtained by Rzayev et al. [55], where they found on-body and floating placements of notifications to be more preferred and usable by the users. The second most preferred placement was the object-anchored placement. These findings support the patterns that we have discussed with the findings of the first research question above with respect to mental workload

and user experience.

Pertaining to the factors affecting these preferences, the qualitative interviews highlighted some interesting aspects associated with these four placements.

Three of the nine participants who had chosen the wrist-anchored placement to be the most preferred mentioned that the object-anchored placement of learning content would have been most preferred by them had it been augmented with cues pointing to the location of the next instruction. We spawned our object-anchored placement of instructions as an extension to McNamara et al.'s [61] work around presenting labels in VR. Their work used an eye-gazing technique to gauge users' attention for identifying objects of interest and placing information labels on them. In contrast, in our case, the position of the instruction panel is intended to guide the eye gaze and thereby the attention of the user to the object of interest (to which the current snip of learning content is associated). Therefore, had this placement been augmented with cues pointing to the next location of the learning content panel, it would have aided/directed the user's attention to the following instructions and made navigation through the tutorial easier for them in turn moving up the object-anchored placement up the ladder of preference.

HMD-anchored placement of learning content even though being specified to be the most convenient and readable was the third preferred placement of learning content. This is analogous to findings from Rzayev et al. [55] where the Head-Up display was the least preferred by the users even though it had the least missed notification count and shortest response time. This was mainly attributed to the obtrusiveness of this placement in both studies. A deeper analysis of our qualitative findings revealed that the obtrusiveness of the HMD-anchored placement only bothered our users during the procedural part of the tutorial where they had to operate the laser cutting machine. For the initial part of the tutorial that taught factual and conceptual content about the laser cutting process and machine, the HMD-anchored placement was in fact liked by the participants. This implies that placement choice is also affected by the type of content being presented in the VR environment.

Finally, in response to our final research question *"Which display placements are more suited to presenting learning content across VRLEs?"*, we found the controller-anchored and object-anchored placements to be more suited for learning environments focused on training procedural content both in terms of user experience and user preferences. However, no significant differences were found in learning outcomes and cognitive load. This low statistical power could be attributed to the participant sample [129] and demands further research in terms of the number of participants and the diversity of participants.

Based on these findings and discussion around spatial representation of learning content in VRLEs we come up with the following recommendations while designing VRLEs:

Proximity of learning content: Learning content placed close to either the user or close to the object of interest in the environment improves the overall user experience. Since constant reference to learning content is important in a learning environment, users prefer it to be in the vicinity of their working area to avoid any additional workload to access the content.

Dynamicity of learning content (to maintain Proximity): Dynamic spatial representations are preferable in immersive VR learning environments as compared to static spatial representations. Users prefer learning content in VRLEs to move rather than them having to perform the additional task of navigating in the environment to refer to the content again and again. One of the main reasons for dislike of the world-anchored spatial representation was the additional task of going back and forth to the TV screen.

Cueing: (to augment dynamicity): Users should be guided as to where the next part of the content be displayed in the environment unless figuring that out is part of the learning process. Finding or determining the location of the upcoming learning content in case of dynamic spatial representation again acts as an additional task for the user, thereby adding to the overall workload and therefore affecting the user experience.

Heads-on display: The most preferable spatial representation for content in context to the goal of the VRLE and which does not require any interaction on the users' part is the

heads-on display. It fulfills both the proximity and dynamicity condition and requires the least effort since it is directly in front of the user. For instance, in our case, the learning content is in congruence with the learning environment, and the factual and contextual content did not require any hands-on task from the user; therefore, for that content, HMD-anchored placement was the most convenient and preferable but not for procedural content. However, in the case of Rzayev et al., [55], the content in consideration were notifications from the real world, which are not in the context of the simulation, thereby making the heads-on display placement not so preferable.

Overall, all recommendations advocate avoidance of the performance of any additional tasks on the part of the immersed participant apart from the tasks required from them with respect to the goals of the VR learning experience. In the follow-up experiment where users had the choice to move the TV screen along with them (which fulfilled both the dynamism and proximity recommendation), they did not prefer the additional task of moving the TV screen around in comparison to spatial representations that moved along with them or moved from one place of action to the other without any intervention on the user's part. Similarly, for object-anchored placement (which also fulfilled the proximity and dynamicity conditions), users preferred not to have the additional task of finding the place of the next instruction. Any additional task tends to increase the user workload, thereby limiting the mental capacity to contribute to learning. Therefore, designers should keep in mind to avoid as much as possible any design elements which do not contribute to the learning goals.

CHAPTER 4
EVALUATING MULTIMEDIA DESIGN PRINCIPLES FOR VERBAL CONTENT IN VRLES

While the previous chapter focused on empirically evaluating an affordance of VR that has been largely overlooked in educational contexts, this chapter shifts attention to an affordance that has been studied in relation to learning outcomes but only under a limited range of moderating factors. Here, I extend this line of inquiry by examining how various moderating factors influence both the effectiveness of this affordance and the corresponding design decisions within VR-based learning environments.

4.1 Motivation

Virtual Reality Learning Environments (VRLEs) enable high-end experiential learning and foster active learning by facilitating diverse modes of information presentation, supporting interactive engagement, and promoting self-directed exploration [130]. To fully harness the affordances of VRLEs and maximize learning outcomes, it is essential to ground their design in robust, research-backed principles [37, 14]. A particularly critical element in this process is the design of verbal content, which plays a central role in communicating concepts, delivering instructions, and providing meaningful feedback within the learning environment. Accordingly, a substantial body of research has established design principles for effectively presenting verbal content in 2D multimedia learning environments. Two key principles are the Modality Principle [131], which focuses on managing cognitive load across different sensory channels, and the Redundancy Principle [132], which explores how presenting the same information across multiple modalities can impact learning. Notably, both principles have also been investigated within the context of immersive 3D learning environments, highlighting their relevance for VRLE design.

However, these works have largely been limited to VRLEs focused on delivering factual and conceptual knowledge. This excludes procedural learning, a crucial capability afforded by VRLEs enabled by their high interactivity [130]. Procedural learning differs from factual and conceptual learning not only in the physical effort it requires, demanding hands-on engagement from the learner, but also in terms of active cognitive processing [133]. In terms of Bloom's taxonomy, while factual and conceptual knowledge primarily engage lower-order cognitive processes such as remembering, understanding, and analyzing, procedural knowledge targets higher-order processes such as applying, evaluating, and creating [134]. As such, design principles originally developed for factual and conceptual content may not directly translate to procedural learning. Moreover, the effects of varying levels of redundancy have not been systematically explored in the context of VRLEs. To address these gaps, this study investigates the relevance and effectiveness of the Modality and Redundancy Principles across factual, conceptual, and procedural content within VRLEs.

In this study, we conducted a mixed-methods investigation using a within-subjects design with 40 participants. We explored the effects of four information presentation modalities—audio only, text only, audio + text (full redundancy), and audio + text (concise redundancy), within a VR learning environment focused on teaching 3D printing concepts and the operation of a 3D printer. These conditions, varying in degrees of redundancy, were tested in VRLEs designed to convey both procedural knowledge (with low and high interactivity) and non-procedural knowledge (factual and conceptual). We adopted a multimodal data collection approach comprising self-report scales, semi-structured interviews, and electrodermal activity (EDA) measurements. This enabled us to triangulate subjective and physiological data to gain deeper insights into users' preferences across the four modes of information presentation. Through this study, we address the following research questions:

1. **RQ1:** How do different modality combinations (textual, aural, and their varying

levels of redundancy) impact users' cognitive load for procedural learning in VR learning environments?

2. **RQ2:** What are users' perceptions and preferences regarding various modality and redundancy combinations in VRLEs?

3. **RQ3:** How do cognitive load, user experience, and perceptions of modality and redundancy combinations differ across procedural and non-procedural knowledge content?

Our triangulated findings revealed a clear participant preference for redundant modalities over single-modality formats, particularly in the context of procedural learning content. Interview data further emphasized a stronger preference for concise forms of redundancy. The audio-only modality was consistently rated as the least preferred and deemed unsuitable for procedural tasks. These insights contribute to the evolving HCI and VRLE literature by providing empirical evidence to inform the design of verbal content representation in virtual learning environments. Secondly we present how these representational preferences vary based on the type of content. Additionally, they offer a nuanced understanding of users' perceptions, experiences, and the challenges they encounter in highly interactive VRLEs,the factors that shape their preferences thereby informing the design of more effective learning experiences.

4.2 Methodology

Our study was approved by the institution's ethics review board. Participants provided informed consent before the experiment and were assured full anonymity. They were compensated for their time with an Amazon gift certificate. Below, we provide a detailed overview of the experiment design, the overall study protocol, the VR simulation used, participant's recruitment and data analysis approach.

Table 4.1: Latin Square Balancing for modality+redundancy conditions

	Part 1 (P1) Types of Manufacturing - factual	Part 2 (P2) Concept of 3D Printing - conceptual	Part 3 (P3) Using 3D Printer Software - procedural(low interactivity)	Part 4 (P4) Operating the 3D Printer - procedural (high interactivity)
Iteration 1	text only (t)	audio only (a)	text + audio: full redundancy (ta_f)	text + audio: partial redundancy (ta_p)
Iteration 2	audio only (a)	text + audio: full redundancy (ta_f)	text + audio: partial redundancy (ta_p)	text only (t)
Iteration 3	text + audio: partial redundancy (ta_p)	text only (t)	audio only (a)	text + audio: full redundancy (ta_f)
Iteration 4	text + audio: full redundancy (ta_f)	text + audio: partial redundancy (ta_p)	text only (t)	audio only (a)

4.2.1 Experiment Design

We employed a within-subjects design with two independent variables with four levels each. The first independent variable, Modality-Redundancy variable had the following four levels—text only (referred to as 't' henceforth), narration only (referred to as 'a'), text plus narration with full redundancy (referred to as 'ta_f'), and text plus narration with partial (concise) redundancy (referred to as 'ta_p'). In the full redundancy condition, the complete text is presented in both textual and audio form. In contrast, partial or concise redundancy presents the full audio but displays only the key points in the form of bullet-points in textual format. The second independent variable, type of knowledge content had the following four levels: factual, conceptual, procedural with low interactivity, and procedural with high interactivity. The VR learning module was structured into four corresponding parts: Part 1 (referred to as P1 henceforth) covered factual content, Part 2 (P2) addressed conceptual content, Part 3 (P3) focused on procedural content with low interactivity, and Part 4 (P4) presented procedural content with high interactivity. Each part of the module was presented to participants using a different modality-redundancy combination. To counterbalance ordering effects, the assignment of modality-redundancy conditions to con-

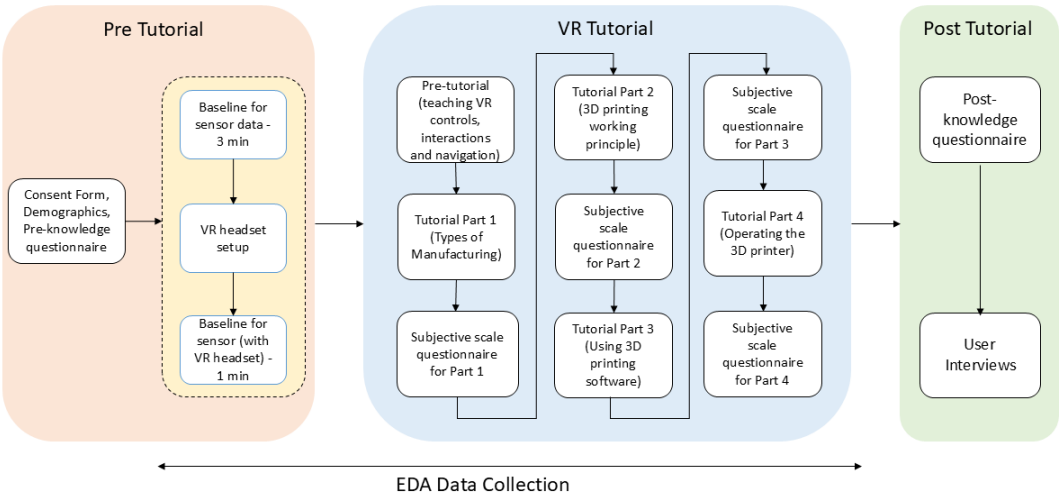


Figure 4.1: The figure illustrates the data collection procedure used in this study, showing the sequence of execution. The diagram includes the following abbreviations for the respective components: VR (Virtual Reality) and EDA (Electrodermal Activity, also known as Galvanic Skin Response).The Subjective Scale Questionnaire encompass the 10 scale cognitive load scale from Leppink [125] and single questions cognitive scales from Paas [121], Ayres [38], Ciernak [123] and Salomon [124]

tent parts was randomized using a Latin square design(see Table 4.1), ensuring that each condition appeared in each position across participants. However, the order of the content itself was kept fixed to preserve the intended learning progression and avoid disrupting the overall user experience.

4.2.2 Procedure

We started the experiment with obtaining informed consent from participants, followed by a pre-session questionnaire that gathered demographic information and self-reported prior experience with VR and the tutorial topic. The pre-session questionnaire also consisted of a set of knowledge-based questions (conceptual, factual, and procedural) on the topic of 3D printing to gauge participants' existing knowledge on the topic. The primary researcher then mounted the EDA sensors (16-channel Biopac MP160 with SS57LA Hardware Module/Biopac MP160 Aquisition System) on the participant and recorded a 3-minute baseline measurement using the sensor. They then positioned the virtual reality (VR) headset on the

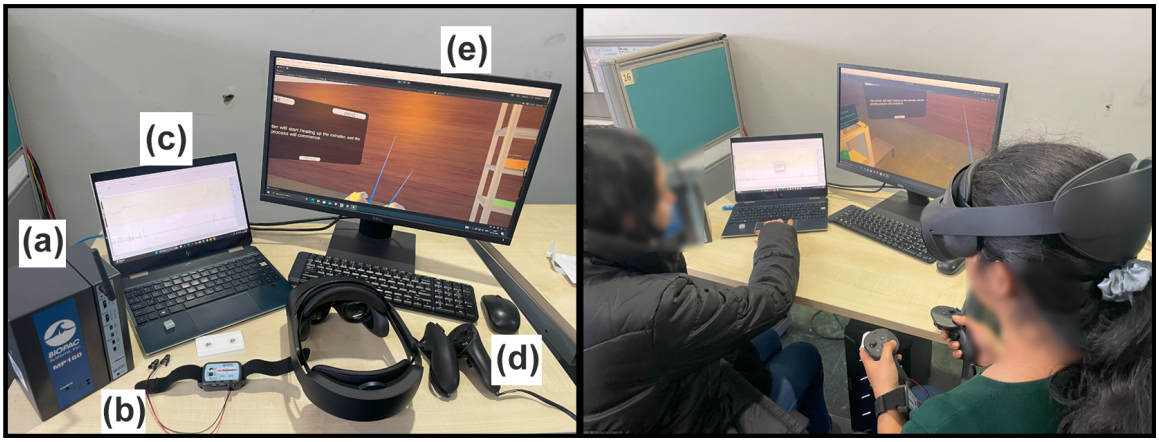


Figure 4.2: The left figure illustrates our experimental setup. (a) Biopac MP160 Aquisition System, (b) Wireless EDA sensors, (c) system with AcqKnowledge 5.0 running for EDA data collection, (d) Oculus Quest Pro VR headset and (e) system connected to headset via airlink for screen recording user interaction with tutorial. The right figure shows a participant performing the experiment.

participant, followed by an additional 1-minute EDA baseline recording to allow familiarizing the user with the VR headset. The VR simulation was initiated after the completion of this period. After exiting the VR simulation, the participants were inquired about any discomfort, followed by the post-task questionnaire to test knowledge gain. The session concluded with a semi-structured interview to understand user preferences and perceptions around the four content and modality-redundancy combinations and their overall experience with the tutorial. The participants were free to stop the experiment or take a break anytime during the experiment. An overview of the procedure can be seen in Figure 4.1 and Figure 4.2 shows a participant performing the experiment.

4.2.3 VR Simulation

We developed a VR simulation in Unity v2020.3.26f1 to support learning about the 3D printing process and its use in lab prototyping. The tutorial comprised four parts, each corresponding to one of the learning content types described earlier. It also included a short pre-tutorial at the beginning, designed as an introduction and training module to familiarize participants with the VR environment. This pre-tutorial guided users on movement using the joystick, teleportation, and interacting with objects in VR. This was followed by the four

parts of the 3D printing tutorial. P1 introduced types of manufacturing (factual content), P2 covered the theory behind 3D printing (conceptual content), P3 explained how to use the 3D printer software (procedural content with low interactivity), and P4 presented a step-by-step guide to operating the 3D printer (procedural content with high interactivity). Figure 4.3 shows the screens from different tutorial parts. Each tutorial part was presented to the user in a different modality-redundancy combination. We developed four versions of the application to cater to the four combinations of modality-redundancy and eliminate any ordering effect in our results. After each part of the tutorial, participants completed in-VR questionnaires to report their perceived cognitive load - covering intrinsic, extraneous, germane, and overall load for that specific section.

The tutorial was administered in English and was learner-paced so participants could move forward and backwards in the tutorial at their own pace and as many times as they desired. Each instruction slide had a Next, Previous and Replay (except in the text-only condition) option for the participant to navigate. The learning content and the knowledge evaluation questionnaires (pre- and post) were validated by our institute's Design and Innovation (DI) Lab engineer, who is the key person responsible for teaching the 3D printer to the students.

4.2.4 Data Collection Instruments

Knowledge Gain

We evaluated the participants' overall knowledge gain to validate our tutorial content and to ensure that the participants actively engaged with the content while in the VR environment rather than simply forwarding through the tutorial without paying attention. We tested participant knowledge related to the topic in both the pre-and post-study questionnaires to calculate the gain in knowledge. The pre-study questionnaire comprised 9 multiple choice questions (For example, a sample question: Which form of manufacturing involves the removal of material from the workpiece to obtain the desired shape?) The post-study ques-

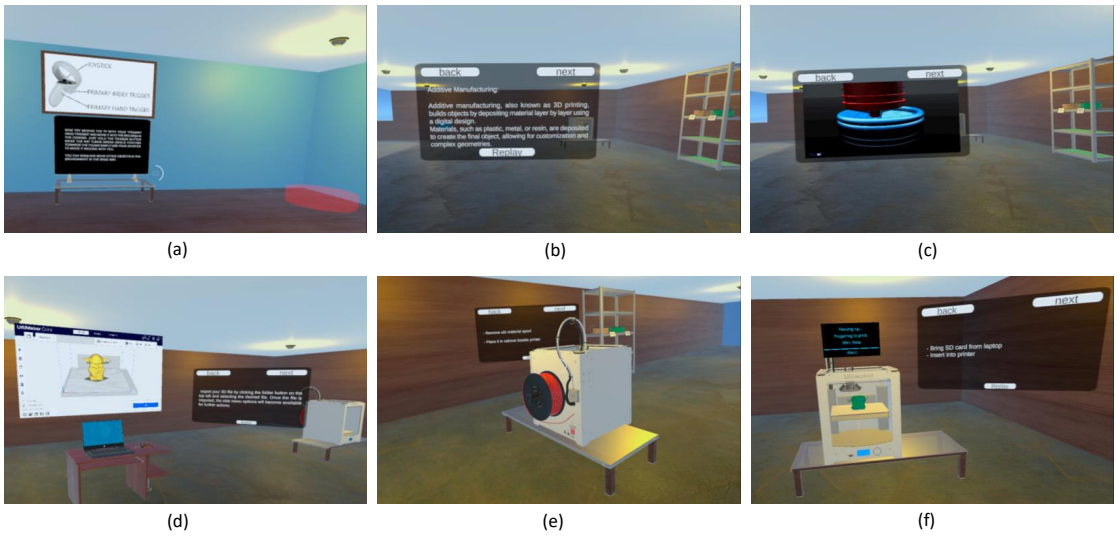


Figure 4.3: The figure illustrates screenshots of the VR tutorial. (a) shows the pre-tutorial, (b) shows the first part containing factual content with text+audio (full redundancy), (c) shows the second part containing conceptual content with only audio modality, (d) shows the third part containing procedural (low interactivity) content with only text modality and (e),(f) show the fourth part containing procedural (high interactivity) content with text+audio (partial redundancy).

tionnaire included 18 multiple-choice questions: 9 repeated from the pre-study questionnaire and 9 new questions derived from the tutorial content. This approach was intended to reduce participant bias by preventing them from focusing disproportionately on parts of the tutorial related to the pre-study questions.

Self-reported Cognitive Load Scales

We used two self-reporting measures to assess participants' cognitive workload during the experiment. The first measure was the 10-item cognitive scale presented by Leppink et al. [125]. The scale comprises three questions each assessing the intrinsic and extrinsic cognitive load and four questions assessing the germane cognitive load. All the responses were collected on an 11-point Likert scale ranging from 0 to 10. We further used the single-question intrinsic cognitive load measure from Ayres [122], the extraneous cognitive load measure from Ciernak et al. [123], the perceived concentration during learning measure from Saloman [124] and the overall mental effort measure from Paas et al. [121] to consolidate our findings. These four items were reported on a 9-point Likert scale.

Electrodermal Activity

We used the 16-channel Biopac MP160 to collect user EDA data using the SS57LA Hardware Module. All experiments were conducted in a dedicated room containing only the experimental setup, the researcher, and the participant. This controlled environment helped maintain consistent temperature and humidity levels while minimizing potential distractions from external factors throughout the data collection process. The participants were seated in a comfortable non-metallic chair (to avoid interference with the EDA signal). The sensors were attached to the user's index and middle finger of the non-dominant hand. We ensured the abrasing of the sensor attachment site, applying isotonic gel and firmly securing the sensors for each participant to minimize noise during the data collection. The data was collected at a sampling frequency of 2000 samples/sec and later down-sampled to 62.5 samples/sec for calculations.

4.2.5 Data Analysis

The study involved four types of data for analysis: responses to knowledge questions to assess learning gains; one 10-item self-report scale and four single-item self-report scales to measure different aspects of cognitive load; EDA data to evaluate participants' arousal levels; and interview data to gain deeper insights into their preferences and the reasoning behind them.

We conducted independent t-tests to assess the increase in overall knowledge and the reduction in 'I don't know' responses between the pre- and post-tutorial questionnaires. The remaining quantitative data was analyzed through three separate analyses. First, we performed a between-subjects analysis to examine the effect of the four modality-redundancy conditions on cognitive load and arousal levels. Although the overall study used a within-subjects design, this additional perspective let us isolate the unique influence of modality-redundancy independent of content-type. Second, we conducted a within-subject interaction analysis to explore the interaction between modality-redundancy and content type. Finally, we re-

peated the within-subjects interaction analysis for subgroups of participants, segmented based on their prior experience with VR to explore potential effects of prior experience, if any.

For the between-subjects analysis of cognitive load, the Shapiro–Wilk test was first employed to assess the normality of the data distributions. Depending on the outcome, either a one-way ANOVA or a Kruskal–Wallis test was conducted, followed by appropriate post hoc comparisons. Since both the within-subject analyses involved two factors with four levels each, we used the Aligned Rank Transform (ART) for the cognitive load measures adapted from Paas, Ayres, Cierniak, and Salomon [121, 122, 123, 124] as they were single item questionnaires. The ten-item cognitive load questionnaire developed by Leppink et al. [125] was also analyzed using ART due to violations of normality assumptions. Post-Hoc pairwise comparisons were done using emmeans with Tukey-corrected contrasts wherever a significant main effect of modality or type of content was observed. For the follow-up interaction contrasts, Holm's sequential correction was applied to adjust p-values and control the family-wise error rate.

EDA data, used to assess physiological arousal, were continuously recorded to capture both tonic (Skin Conductance Level, SCL) and phasic (Skin Conductance Response, SCR) components. The signals were preprocessed to remove motion artifacts, downsampled from 2000 Hz to 62.5 Hz using AcqKnowledge 5.0, smoothed, and then separated into tonic and phasic components. To enable comparability across participants, the data were z-normalized, and statistical analyses were performed on the SCR component, which is widely regarded as a reliable indicator of cognitive load. This measure is henceforth referred to as ZnormalSCR in the thesis. Due to the non-parametric nature of the data, the Aligned Rank Transform (ART) method was used for analysis. The same statistical procedures were applied in the subgroup analysis based on participants' prior VR experience, for cognitive load as well as EDA data, as normality assumptions were again not met.

For the qualitative analysis, the interviews were first transcribed and translated by the

first author (thesis author). We then conducted an iterative thematic analysis following the approach outlined by Braun and Clarke [135]. In the initial coding phase, the first author independently carried out line-by-line coding of all transcripts. These initial codes were subsequently reviewed and collaboratively refined by the thesis author in consultation with the co-authors of the respective study to identify broader themes.

4.2.6 Participants

We recruited 49 university students to participate in the study (37 males, 12 females, 0 non-binary, mean age = 21.1 years, SD = 2.64). Participants signed up for our study through an invitation mail shared across the university mailing lists. Nine participants failed to complete the experiment due to discomfort from simulator sickness symptoms while using the VR headset. The participants were required to be older than 18 and fluent in English. They had a mean self-reported experience with VR of 2.36 (from 1 = Not at all experienced to 5 = Extremely experienced). Their mean familiarity with the topic of 3D printing was 2.68, while the mean familiarity with 3D printer usage was reported to be 1.71 (from 1= Not at all familiar to 5 = Extremely familiar).

4.3 Findings

We start this section by presenting the results of the knowledge gained to establish the relevance and feasibility of our tutorials and the experiment. We then discuss our findings from the self-reported scales and the EDA measurements, followed by our findings from the user interviews. We triangulate the data by relating the interview findings to the self-reported scales and EDA measurements, drawing connections where they provide complementary insights or help explain the underlying rationale for the observed results.

4.3.1 Knowledge Gain

We observed a statistically significant increase in knowledge gained (t = 8.6963, p <0.00001, d=1.38) where the average percentage knowledge score on the pre-study questionnaire was 26.66% (2.4 out of 9), while that on the post-study questionnaire was 55.27 % (9.95 out of 18). The large effect size indicated a substantial improvement in participants' knowledge following the study.

Similarly, there was a statistically significant decrease in the number of responses marked "I don't know" (t= 8.34, p <.00001, d = 1.32). The average percentage of "I don't know" responses dropped from 46.38% (4.179 out of 9) to 6.38% (1.15 out of 18) between the pre- and post-study questionnaires. The very large effect size, highlighted a considerable reduction in uncertainty or lack of knowledge.

4.3.2 Self Reported Scales

In the between-subjects analysis examining the effect of modality within each part of the tutorial, a statistically significant difference in extraneous cognitive load was found only in P3 (p = .008, ϵ^2 = 0.24, large effect). Post-hoc Wilcoxon rank-sum tests with Holm correction indicated that both full redundancy and partial redundancy conditions resulted in lower extraneous load compared to the audio-only condition (p = .011 and p = .055, respectively). Specifically, the audio-only group reported the highest mean extraneous load (M = 4.5, SD = 1.17), followed by the partial redundancy group (M = 3.0, SD = 1.00), while the full redundancy group reported the lowest (M = 2.4, SD = 1.07). The large effect size suggests a strong, practically meaningful impact of modality on extraneous load in P3. Additionally, the study was adequately powered (83%) to detect effects of this magnitude with a sample size of 40.

For the within-subjects interaction analysis, the main effect of modality-redundancy combinations were observed on both overall mental effort and extrinsic cognitive load. A statistically significant main effect of modality on overall mental effort was found (p =

0.0243, η^2p = 0.085 (medium), f = 0.31, power $\approx$ 0.70). Post hoc pairwise comparisons revealed that this effect was primarily driven by a significant difference between the audio-only and text-only conditions (p = 0.0199). We also found a marginally significant main effect of modality on extrinsic cognitive load (p = 0.073, η^2p = 0.064 (medium), f = 0.262, power $\approx$ 0.53), with post hoc analysis indicating a significant difference between the audio-only and partial redundancy (text + audio concise) conditions (p = 0.0464).

Furthermore, a statistically significant interaction effect was observed between content type and modality-redundancy for extrinsic cognitive load (p = 0.0019, η^2p = 0.21 (large), f = 0.216, power $\approx$ 0.88). Post hoc analysis of this interaction revealed significant differences between the audio-only and full redundancy conditions across different content types—specifically for P2 (conceptual content) and P3 (procedural content with low interactivity) (p = 0.02616), indicating that the effectiveness of modality-redundancy combinations varies depending on the nature of the content.

A significant main effect of content type was observed across all subscales of cognitive load, as measured by Leppink et al.'s questionnaire [125]. Specifically, intrinsic load (p = 8.44e-07, η^2p = 0.255 (large), f = 0.585, power $\approx$ 0.97), extrinsic load (p = 1.04e-06, η^2p = 0.252 (large), f = 0.58, power $\approx$ 0.99), and germane load (p = 0.0207, η^2p = 0.088 (medium), f = 0.31, power $\approx$ 0.77) all showed statistically significant differences based on the type of learning content. Post hoc pairwise comparisons for intrinsic load revealed significant differences between P1 and P2 (p = 0.0023), as well as between each of the first three parts and P4 (P1 vs P4: p $<$0.0001; P2 vs P4: p = 0.0159; P3 vs P4: p = 0.0021), suggesting a notable increase in intrinsic cognitive load during the highly interactive procedural segment.

Similarly, significant main effects of content type were also found in all the single-item cognitive load scales: intrinsic (p = 8.51e-06, η^2p = 0.22 (large), f = 0.53, power $\approx$ 0.98), extrinsic (p = 0.00015, η^2p = 0.175 (large), f = 0.462, power $\approx$ 0.91), and germane (p = 0.0252, η^2p = 0.085 (moderate), f = 0.305, power $\approx$ 0.73), and for the mental effort scale

(p = 6.34e-07, η^2p = 0.259 (large), f = 0.59 , power >0.99). Post hoc analyses confirmed that the fourth part (highly interactive procedural content) elicited significantly different responses compared to the other three parts across most scales. In the case of germane cognitive load, a significant difference was also observed between P2 (conceptual content) and P4 (p <0.05). Corresponding box plots and interaction plots for mental effort, intrinsic, extrinsic, and germane cognitive load can be found in Figure 4.4, Figure 4.5, and Figure 4.6 at the end of this chapter.

To further deepen our analysis, we segmented participants into two groups based on their self-reported prior experience with VR, as indicated in the pre-tutorial questionnaire. Group 1 (referred as G1 henceforth) included participants who rated their prior VR experience as 1 or 2 on a 5-point scale, indicating low or no exposure. Group 2 (referred as G2) comprised those who rated their experience as 3 or above, reflecting moderate to high exposure. The same statistical tests were conducted separately for each group. For G1, we observed statistically significant main effect of modality for germane cognitive load (p=0.021). Post hoc comparisons revealed that these effects were driven by significant differences between the audio-only and text-only conditions (p = 0.0492). For this group, statistically significant main effect of type of content was reflected across both intrinsic load measures (intrinsic load Leppink scale: p=8.225e-06; intrinsic load Ayres scale: p=1.013e-05), overall mental effort (p=1.002e-06) and germane cognitive load(p=0.047). Post hoc analysis attributed all these differences majorly to the differences in cognitive load between each of the first three parts and P4 (detailed p values in Table 4.2. Notably, for G2, statistically significant interaction was only observed in the case of extrinsic cognitive load due to an interaction effect of modality X type of content (p=0.003). Post-hoc analysis revealed significant differences for only audio and full redundancy conditions between Parts P1–P2 (p = .039), P1–P4 (p = .010), P2–P3 (p = .035), and P3–P4 (p = .008). An overview of all subjective scale results is provided in Table 4.2. Corresponding box plots and interaction plots for mental effort, intrinsic, extrinsic, and germane cognitive load can

be found in Figure 4.7 through Figure 4.12 at the end of this chapter.

4.3.3 EDA Data

We applied the same three analyses to the EDA data as to the self-reported cognitive load measures. The first analysis examined the independent effect of modality-redundancy combinations on users' SCR (Skin Conductance Response) values across individual tutorial parts. This analysis did not reveal any statistically significant effects.

The second analysis investigated the interaction effect of modality-redundancy and the type of knowledge content on overall cognitive load. Although no significant main effect was found for modality-redundancy, we observed a statistically significant main effect of content type on SCR values (p = 1.3677e-06, η^2p = 0.26 (large), f = 0.586, power $\approx$ 0.99). Post hoc comparisons revealed that these differences were driven by significantly higher SCR values in P4 (procedural content with high interactivity) compared to P1 (factual, p $<$.0001), P2 (conceptual, p = 0.0313), and P3 (procedural with low interactivity, p $<$.0001). The results are illustrated in Table 4.2. The box plots and the interaction plots for the Znormal SCR mean can be seen in Figure 4.4, Figure 4.5 and Figure 4.6 at the end of this chapter.

In a follow-up analysis, with participants segmented based on their prior experience with VR, a statistically significant main effect of modality-redundancy on SCR values was observed (p = 0.0014, η^2p = 0.233 (large), f = 0.55, power $\approx$ 0.92) for G2. Post hoc analysis revealed a significant difference between the full redundancy and text-only conditions (p = 0.0098). Additionally, the type of content showed a significant main effect on SCR values in both groups—G1 (p = 0.0056, η^2p = 0.229 (large), f = 0.544, power $\approx$ 0.94) and G2 (p = 0.0014, η^2p = 0.325 (very large), f = 0.69, power $\approx$ 0.97). Post hoc comparisons indicated that these effects were driven by differences between P1 and P4 (G1: p = 0.0305, G2: p = 0.0039) and between P2 and P4 (G1: p = 0.0050, G2: p = 0.0025). The box plots and the interaction plots for the Znormal SCR mean can be seen in Figure 4.7 through Figure 4.12 at the end of this chapter.

Table 4.2: Overview of Self-reported scales and EDA Results

	Moderating Factor	Participant group	Modality Main Effect	Post-hoc	Part Main Effect	Post-hoc	Modality X Part Interaction Effect	Post-hoc
Self-reported scale	Intrinsic Load Mean (Leppink)	Overall	No effect	NA	**p= 8.4437e-07**	**P1 - P2 (p=0.0233) P1 - P4 (p=<.0001) P2 - P4 (p=0.0159) P3 - P4 (p=0.0021)**	No Effect	NA
		G1	No effect	NA	**p=8.2252e-06**	**P1 - P2 (p=0.0278) P1 - P4 (p=<.0001) P2 - P4 (p=0.0297) P3 - P4 (p=0.0047)**	No Effect	NA
		G2	No effect	NA	No effect	NA	No Effect	NA
	Extrinsic Load Mean (Leppink)	Overall	No effect	NA	**p=1.0411e-06**	**P1 - P2 (p=0.0010) P1 - P3 (p=0.0407) P1 - P4 (p=<.0001) P3 - P4 (p= 0.0130)**	No Effect	NA
		G1	No effect	NA	No effect	NA	No Effect	NA
		G2	No effect	NA	No effect	NA	No Effect	NA
	Germane Load Mean (Leppink)	Overall	No Effect	NA	**p=0.020689**	**P2 - P4 (p=0.0301)**	No Effect	NA
		G1	No effect	NA	No Effect	NA	No Effect	NA
		G2	No effect	NA	No Effect	NA	No Effect	NA
	Mental Effort (Paas)	Overall	**p=0.024303**	**a - t (p= 0.0199)**	**p=6.3411e-07**	**P1 - P2 (p=0.0526) P1 - P3 (p=0.0447) P1 - P4 (p=<.0001) P2 - P4 (p=0.0046) P3 - P4 (p=0.0056)**	No Effect	NA
		G1	No effect	NA	**p= 1.0025e-06**	**1 - 3 (p=0.0267) P1 - P4 (p=<.0001) P2 - P4 (p=0.0001) P3 - P4 (p=0.0115)**	No Effect	NA
		G2	No effect	NA	**p= 0.037736**	**P1 - P4 (p=0.0369)**	No Effect	NA
	Intrinsic Load (Ayres)	Overall	No Effect	NA	**p= 8.5111e-06**	**P1 - P4 (p=<.0001) P2 - P4 (p=0.0078) P3 - P4 (p=0.0180)**	No Effect	NA
		G1	No effect	NA	**p=1.0136e-05**	**1 - 2 (p= 0.0383) P1 - P4 (p=<.0001) P2 - P4 (p=0.0232) P3 - P4 (p=0.0103)**	No Effect	NA
		G2	No effect	NA	No effect	NA	No Effect	NA
	Extrinsic Load (Cier-nak)	Overall	**p=0.07351201**	**a - ta_p (p=0.0464)**	**p= 0.00014573**	**P1 - P2 (p=0.0040) P1 - P4 (p=0.0002) P3 - P4 (p=0.0426)**	**p= 0.00191157**	**a-ta_f : P2 - P3 (p=0.02616 *)**
		G1	No effect	NA	No effect	NA	No Effect	NA
		G2	No effect	NA	No effect	NA	**p= 0.0037038**	**a-ta_f : P1 - P2 (p=0.038997 *) a-ta_f : P1 - P4 (p=0.010091 *) a-ta_f : P2 - P3 (p=0.035294 *) a-ta_f : P3 - P4 (p=0.008193 **)**
	Germane Load (Sa-lomon)	Overall	No Effect	NA	**p= 0.025222**	**P2 - P4 (p=0.0270)**	No Effect	NA
		G1	**p=0.021105**	**a-t (p=0.0492)**	**p= 0.047300**	**P2 - P4 (p=0.0330)**	No Effect	NA
		G2	No effect	NA	No effect	NA	No Effect	NA
EDA	Znormal SCRMean	Overall	No effect	NA	**p=1.3677e-06**	**P1 - P4 (p=<.0001) P2 - P4 (p=<.0001) P3 - P4 (p=0.0313)**	No Effect	NA
		G1	No effect	NA	**p=0.0056056**	**P1 - P4 (p=0.0305) P2 - P4 (p=0.0050)**	No Effect	NA
		G2	**p = 0.0148824**	**ta_f - t (p=0.0098)**	**p= 0.0014114**	**P1 - P4 (p=0.0039) P2 - P4 (p=0.0025)**	No Effect	NA

4.3.4 Interview Findings

In this section, we present the qualitative findings derived from post-study interviews with participants, offering deeper insights into their experiences and perceptions. We begin by exploring user preferences regarding the modality-redundancy combinations, directly addressing one of our core research questions. We then examine participants' reflections on different content types, particularly in relation to cognitive load. Through this discussion, we aim to triangulate and contextualize our quantitative results with qualitative narratives, providing a more holistic understanding.

Modality and Redundancy Preferences

Interview data revealed that participants least preferred the audio-only modality among the four modality-redundancy combinations. This was consistent with our quantitative findings also wherein audio was rated to have imparted the highest extrinsic cognitive load and overall mental effort. Participants attributed this mainly to the higher mental effort and concentration demanded in case of only audio to comprehend learning content. They found the audio-only modality least effective in capturing their attention, which led to reduced focus when content was presented in this format. As one of the participants, P47 mentioned *"..in the first part where it was complete audio, nothing to imagine or to see. It was very boring for me."* The participants also felt that it was easy to get distracted in this case which eventually led to missing the audio instruction. They felt this became even more likely when immersed in VR, as the environment demands active exploration and hands-on interaction, which can divert attention away from the instructional content being played. We found this feedback more prominently from participants who were provided the audio-only modality for later parts of the experiment, which were more procedural in nature. As one of the participants highlighted,

...so sometimes you are looking somewhere else and audio moved ahead or

it told us some initial steps on the printer and we started looking at the step initially but it is continuing ahead, but we have come to perform the previous part of the step... (P21)

Even though the replay instruction option was available to accommodate for missed instructions in the case of only audio, participants did not find it very useful since they were required to go through the complete instruction again, even if a part of the instruction was missed. They found this to be more demanding in terms of effort compared to other modality redundancy combinations. For them, redundancy in modality was a better solution to revisit pointers if any were missed while listening to the audio. As P1 mentioned *"in replay it was like that maybe i have missed two words but i will have to listen from the start. "* Therefore, participants claimed only audio demanded higher effort and increased difficulty, making it more stressful for content consumption and thereby reducing the overall interest of participants.

Our findings further indicated that the audio-only modality demands the greatest level of personalization support to meet individual user needs ranging from pace, voice preferences, accent, and replay options. These properties vary for every user, and a wide array of options must be accommodated for each property to make the experience likeable for a broader range of participants. We found that many of our participants disliked the voice we used and found the pace or accent uncomfortable, which negatively impacted their experience with the audio modality condition. As P31 mentioned, *The voice one was very bad, I did not have any interest in that...I did not like the voice at all.*

Finally, the uncertainty associated with only audio modality around factors like the upcoming content and the amount of content left to be played were some other factors some participants highlighted as shortcomings of using this modality in isolation. As P49 mentioned *"... we are not able to predict that the content is coming, when to press next."*

The interview findings also supported our quantitative results around the preference for modality redundancy, with a majority of participants (24 out of 40) expressing a prefer-

ence for redundant modality combinations over single-modality presentations for delivering learning content in VR. Participants highlighted several benefits of using redundant modalities in VR learning environments. They felt that presenting information through multiple channels helped compensate for the limitations of individual modalities, allowing learners to access and process content more effectively.

> *"The best part was the text with the subtitle thing because... if I missed something or to be heard, I could easily read the previous part on the screen." (P32)*

Redundancy served as additional feedback, reinforcing key learning points and supporting better retention. It provided a means for verifying their own understanding, enabling learners to cross-check the information across modalities. As a result, it significantly enhanced their overall understanding of the content. As P40 mentioned, *"...my strategy was more like this, I was reading on my own and after that I was listening whether I have read the correct thing or not."* Many participants noted that redundancy aided visualization, helping them grasp abstract or complex ideas more easily. As indicated by P36, *"I think when the both are actually implemented onto the subject... it helps in visualizing at the back of the mind also."* It also contributed to an enhanced sense of presence, making the virtual experience feel more immersive and engaging. Beyond cognitive gains, participants reported that redundancy helped eliminate boredom, keeping them more engaged throughout the experience. As P37 stated *"...if we are listening and reading the same thing, then it is more like active. Our brain is more active at that point."* Finally, participants expressed that the availability of redundant cues helped reduce stress, as they felt less pressure to rely on a single source of information and more freedom to explore the environment at their own pace.

Participants particularly valued modality redundancy within VR environments because it enabled greater freedom of exploration without compromising their access to critical information, something they struggled with when relying solely on audio. By presenting content in multiple formats, redundancy reduces the cognitive burden of constantly trying

to retain or recall spoken instructions while navigating the immersive space.

> *The best part was the text with the audio thing because it actually gives a feeling of presence even if you are roaming around...busy exploring the things... so that was something that I really liked. (P32)*

This benefit was especially pronounced for procedural tasks, where learners needed to stay focused on physical interaction and task execution. In such scenarios, redundancy allowed them to shift their attention from reading or memorizing instructions to performing actions more confidently and effectively, thereby enhancing both engagement and performance.

> *I prefer the one with text and audio because let's say I want to do something and the screen is not right in front of me... I can just listen and do the task. I don't have to go, reread it to do it. (P34)*

Of the 24 participants who preferred redundancy, 17 favored concise over full redundancy. They felt that concise redundancy made learning more efficient and focused, helping them grasp essential information quickly without the need to process the full content. P2 mentioned *"So lets say I heard 4 points, but missed the 5th point, I will quickly see the bullet points. But if I have to read paragraph, I will have to find which one is missed."* This approach was seen as less mentally demanding and helped reduce gaps caused by missing either the audio or the text alone. Participants also noted that concise redundancy mirrored real-world learning habits, which made the experience more intuitive and relatable. As mentioned by P37, *"Umm... because I make notes in the same way, in bullet points."*

Effect of Type of Content

Our interview findings reinforced the results from the statistical analysis of the subjective scales and EDA signals, both of which indicated increased mental effort during the final part of the tutorial. Participants consistently described this procedural segment where they were required to operate a 3D printer through hands-on interaction as more challenging

than the earlier sections that involved simply reading or listening to information about its functioning. As P4 stated, *"In the second two parts which involve like actually doing the practical, and like performing tasks, I found that a bit tough to do as compared to like just learning about the concepts." (P4)*

On investigating further to understand particular aspects of the procedural content that participants found difficult, nearly all participants attributed the difficulty not to the tutorial content itself, but to the physical interaction and movement required within the VR environment. Many cited the novelty of VR and the steep learning curve associated with navigating and manipulating virtual objects as the primary sources of cognitive load.

> *"I would say the the moving around part like, that required a little more mental effort compared to the others... the trigger releasing and holding part for putting the SD card or like carrying the spool or the pliers...having to hold that and release it at the correct moment." (P29)*

Importantly, participants acknowledged these as temporary hurdles, expressing confidence that greater familiarity with VR would reduce these difficulties over time. They also suggested that improved motion control, more precise interactions, and shorter tutorials could further ease the experience and lower mental effort.

Despite the reported complexity of the final sections, participants believed these parts offered the most meaningful learning. They consistently reported that the procedural elements especially those involving hands-on tasks such as changing materials, inserting the SD card, and operating the printer deepened their understanding of the topic and were more valuable than the earlier factual and conceptual parts. As P1 mentioned *"...and the fourth part. That was one thing is that was very useful, more understanding was build during it as compared to the first two parts but it was a little difficult also."* This increased learning was attributed to the experiential and interactive nature of these segments, which not only made the tutorial more engaging but also fostered greater interest and sustained attention. As P33 mentioned *"the software use and the final activity we did to print in the 3D printer*

was hands on experience so that was much better."

Participants highlighted that the interactivity involved in performing real-world-like actions within the VR environment made the learning process more enjoyable and impactful. Many noted that this type of learning better captured their attention and helped them stay focused, which in turn improved retention and comprehension. As P7 mentioned *"when I was using the 3D printer, I was the most attentive because I was learning a thing and I was involved in it, my brain was involved in it."* This heightened interest and higher attention was further believed by the participants to be responsible for longer retention of the content.

Furthermore, they emphasized the practical benefits of procedural learning, particularly how it helped bridge the gap between virtual instruction and real-world application. The familiarity of the VR experience with the actual operation of a 3D printer made it easier for participants to replicate the task outside the tutorial, reinforcing the importance of hands-on, immersive approaches to skill-based learning. As mentioned by P5, *"I know and I felt confident that I would be able to perform the same task if asked. It was very close. That is what for a person who has even done for the first time,it would give them a lot of confidence."*

4.4 Discussion

This study examines the application of two foundational multimedia design principles, the Modality Principle and the Redundancy Principle, within immersive VRLEs, across different types of knowledge content. We reflect on the key findings in relation to our research questions, highlight how they contribute to advancing current understanding in the field, and discuss their implications for the design of VR-based learning.

Our findings, both qualitative and quantitative, revealed a clear participant preference for redundant modality combinations, particularly for procedural content. The self-reported data showed significantly lower extraneous cognitive load in redundancy conditions com-

pared to the audio-only condition, which was also identified in interviews as the least preferred format. These results diverge from established principles in 2D multimedia learning, where audio is typically viewed as the least cognitively demanding and redundancy is often associated with increased cognitive load [136]. They also contrast with prior findings from 3D immersive environments involving factual and conceptual content, where redundancy has been shown to reduce extraneous load compared to text, but not significantly in comparison to audio, based on self-reported measures [49, 50]. Furthermore, our findings indicated a consistent preference for concise redundancy, which was associated with significantly lower extraneous cognitive load across all content types, both in self-reported measures and interview responses.

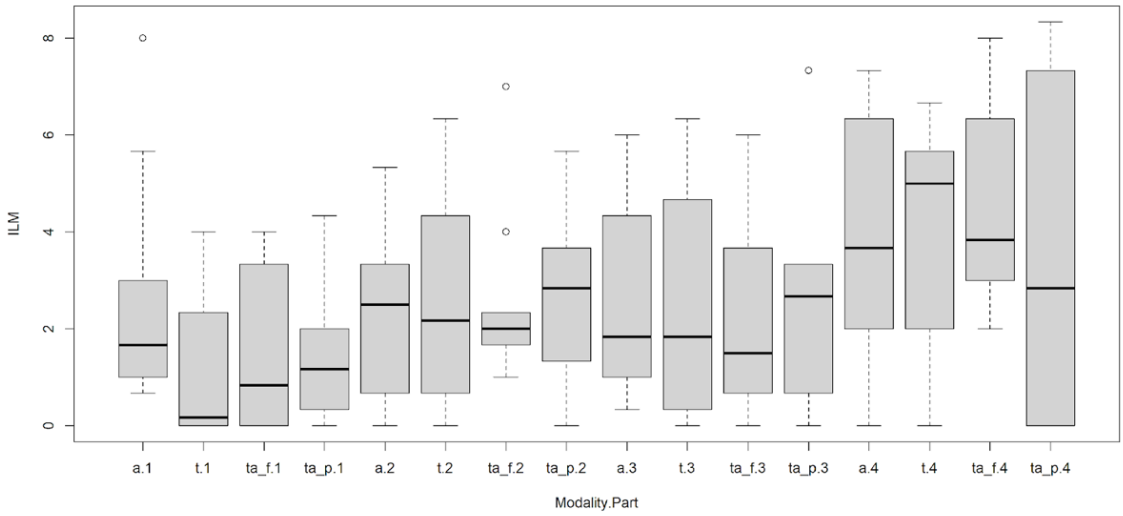
Interestingly, prior evaluations in 3D immersive environments have reported results contrasting with self-reported scales when using EEG data, showing that audio leads to significantly lower cognitive load compared to both text and redundant conditions. While our self-reported data for procedural content indicated otherwise as participants rated audio as inducing the highest extraneous cognitive load, we were unable to validate these findings using our EDA data. This was likely due to the dominant influence of content type (procedural vs. non-procedural) on participants' overall cognitive load and therefore, corresponding arousal levels. This interpretation is supported by both our interview data and the significant main effect of content type in the interaction analysis of self-reported scales, an analytical layer not explored in prior studies. Specifically, the high interactivity section of the tutorial was consistently perceived as more cognitively demanding, regardless of modality, underscoring the critical role of task complexity and interaction demands in shaping learners' experiences in VR.

Another key observation was that the increased cognitive load associated with the type of content, reflected as the main effect of Part or type of content in the self-reported scales, was primarily attributed, according to interview data, to the learning curve required to navigate the VR medium itself (e.g., movements and interactions). Interestingly, this load was

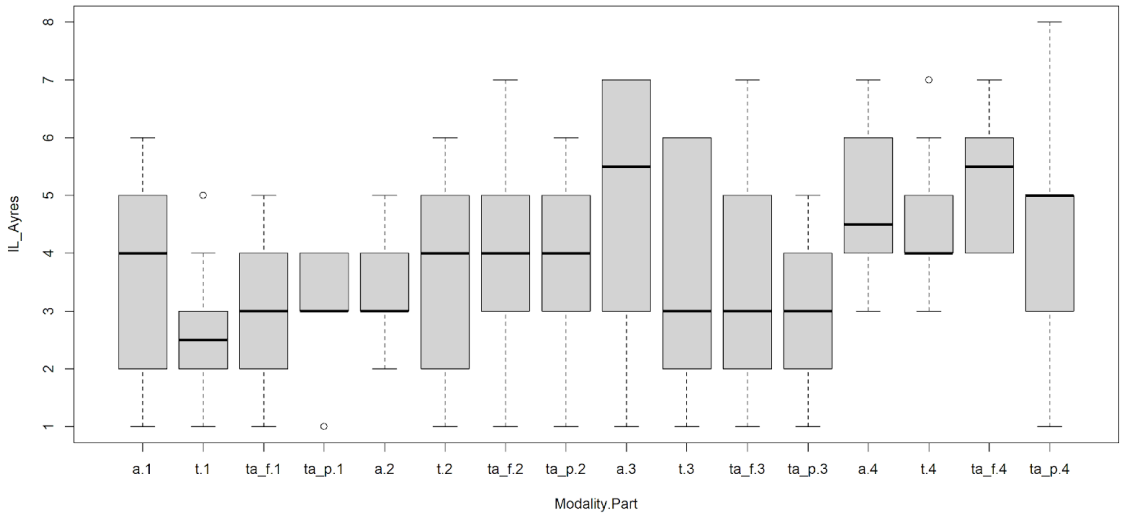
not confined to the extraneous category, as theory might suggest [137], but was instead distributed across intrinsic, extraneous, and germane load sub scales in our self-reported scales measurements. This diffusion of responses points to a limitation in standard cognitive load assessment tools, which often lack the specificity to isolate the load introduced by the learning medium. Without targeted items that address challenges unique to VR, participants may have inadvertently spread their responses across categories, resulting in a blurred depiction of cognitive demands. This ambiguity in load attribution may also partly explain why past studies have yielded inconsistent or contradictory findings around optimal modality configurations in VR-based learning when multiple evaluation mediums are used in conjunction. As immersive technologies like VR become more central in educational contexts, this highlights the urgent need to refine existing measurement frameworks to better capture the distinct cognitive challenges posed by such environments.

Additionally, the consistently high load attributed to VR interaction underscores the importance of reducing extraneous demands through both design and training. Many earlier VRLE studies assumed learners could "drop in" and interact fluently, which may explain contradictory results across experiments. We argue that effective VR instruction requires (a) on boarding sequences that acclimate users to locomotion, object manipulation, and interface conventions; and (b) fine-grained controls—pause, rewind, sectional audio replay—so learners can regulate pace.

In sum, our work advances the field by (1) demonstrating that redundancy can lower cognitive load and improve learner preference in procedural VR tasks, (2) concise redundancy can lower the cognitive load overall across all types of content, (3) highlighting the need for revised cognitive-load measures to cater to medium specific needs, and (4) emphasizing user training and adaptive controls as critical design levers for future VRLEs.

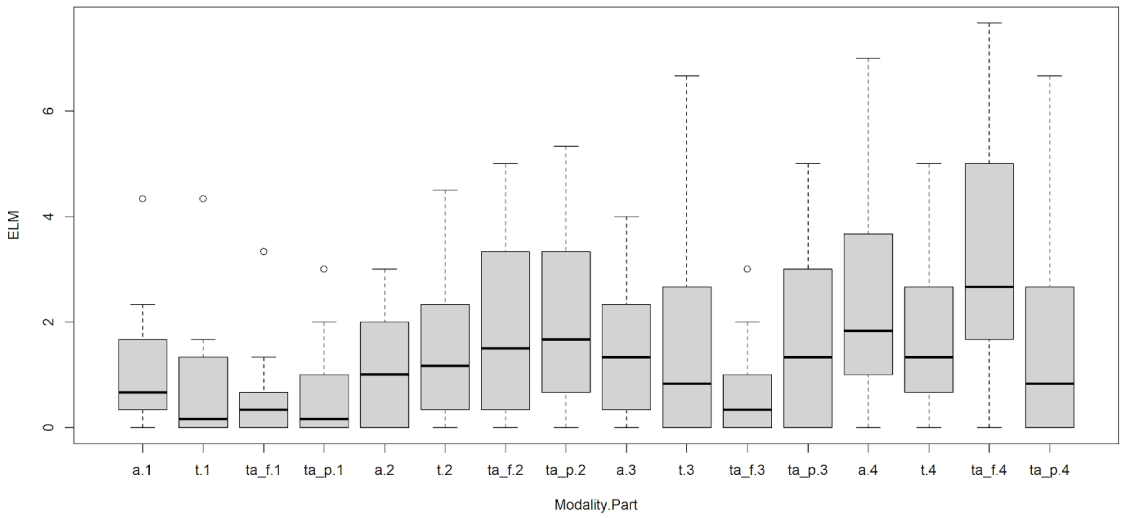


(a) Intrinsic Load Mean (ILM-Leppink)

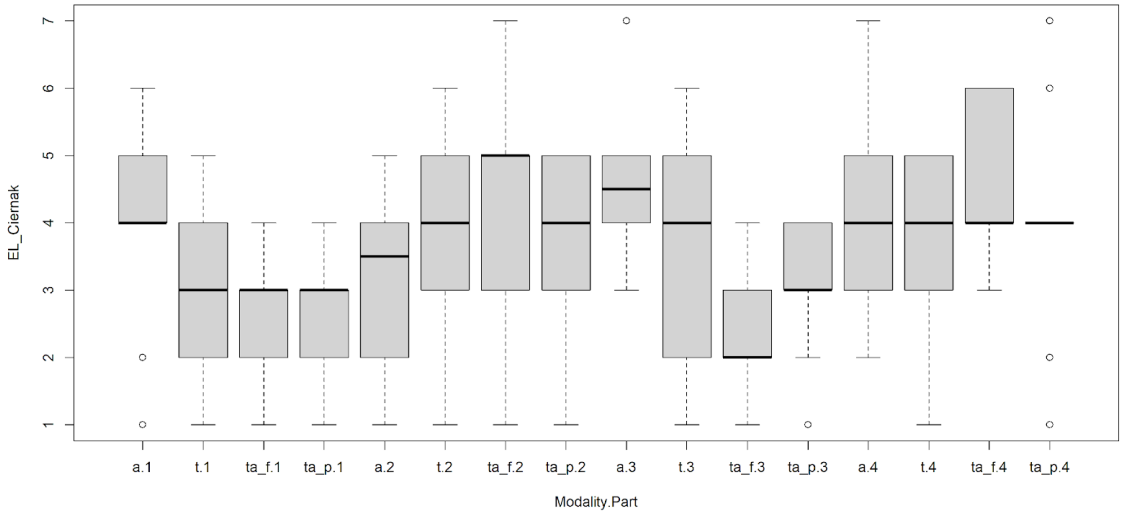


(b) Intrinsic Load (IL-Ayres)

Figure 4.4: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values for Test 2- mixed interaction effect of modality-redundancy X type of content on users' cognitive load.

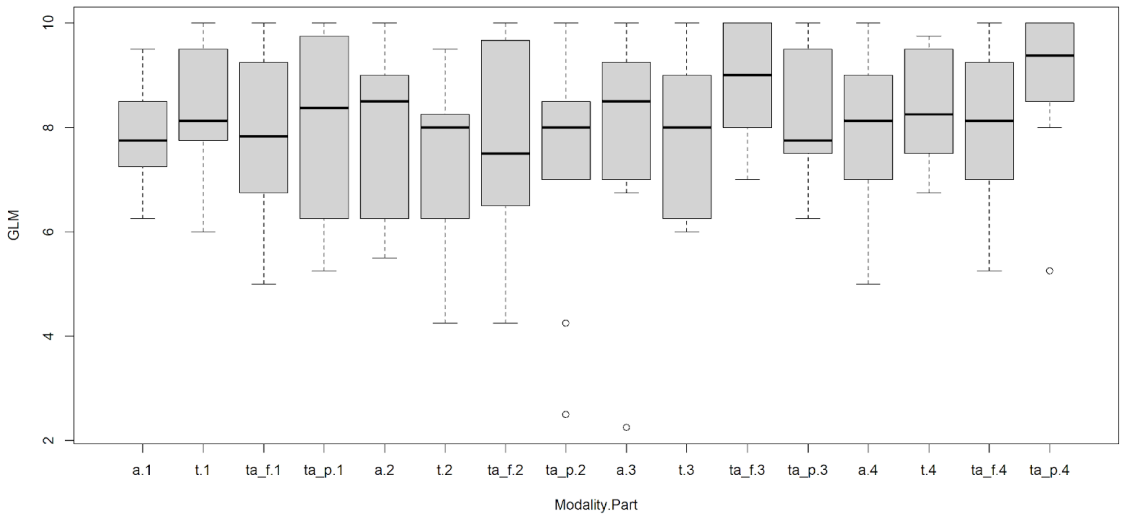


(c) Extrinsic Load Mean (ELM-Leppink)

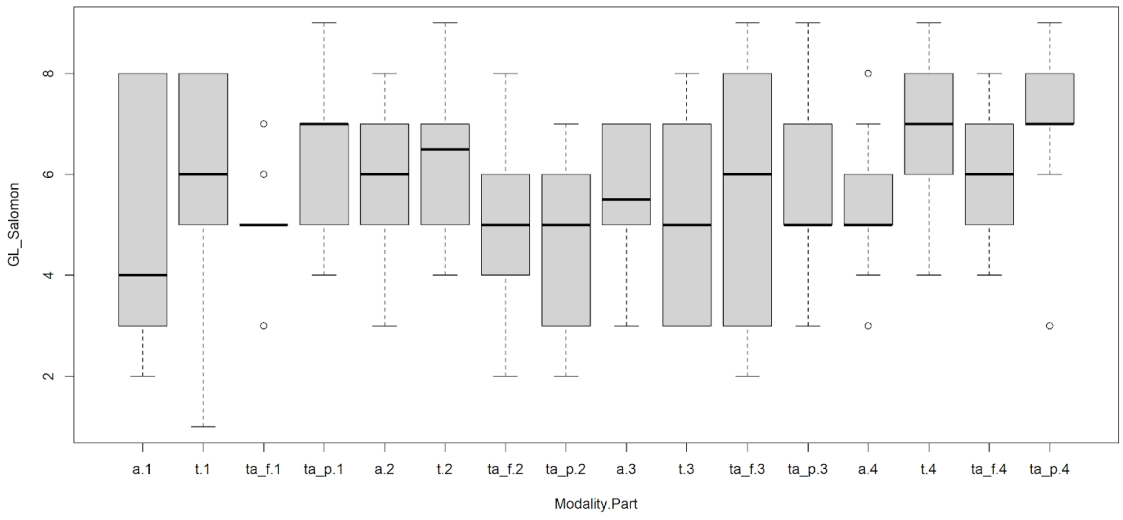


(d) Extrinsic Load (EL-Ciernak)

Figure 4.4: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values for Test 2- mixed interaction effect of modality-redundancy X type of content on users' cognitive load.

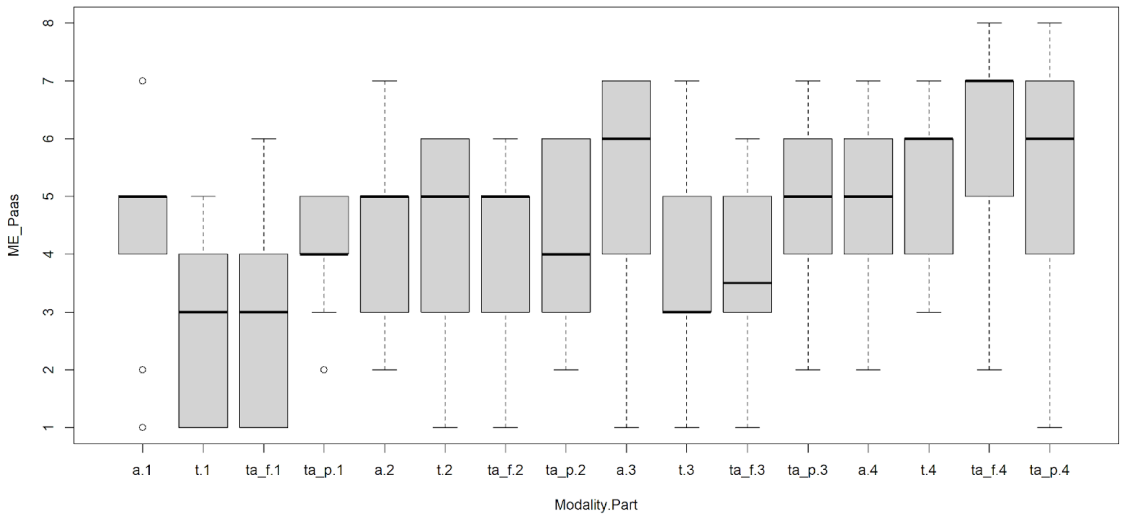


(e) Germane Load Mean (GLM-Leppink)

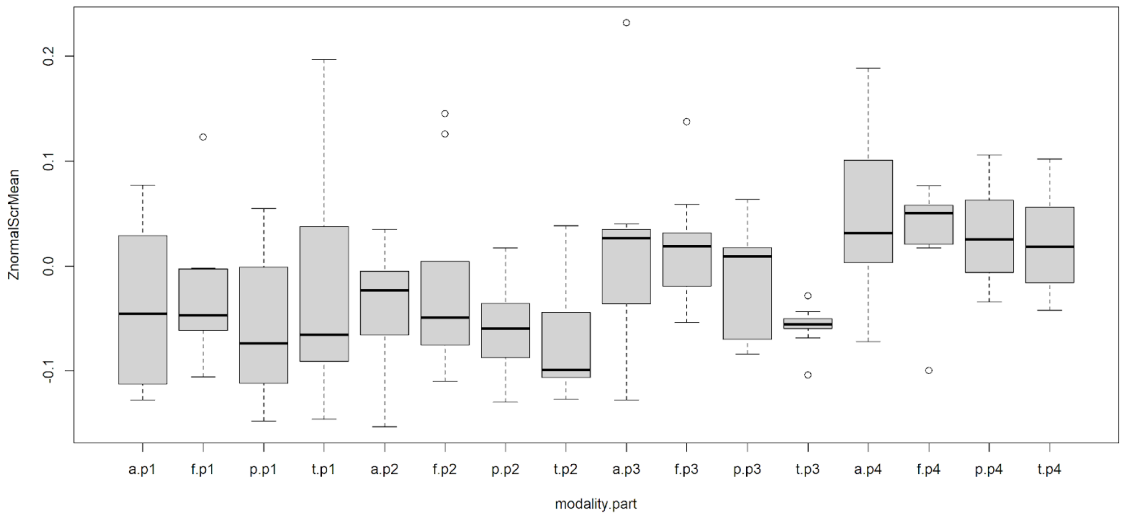


(f) Germane Load (GL-Saloman)

Figure 4.4: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values for Test 2- mixed interaction effect of modality-redundancy X type of content on users' cognitive load.

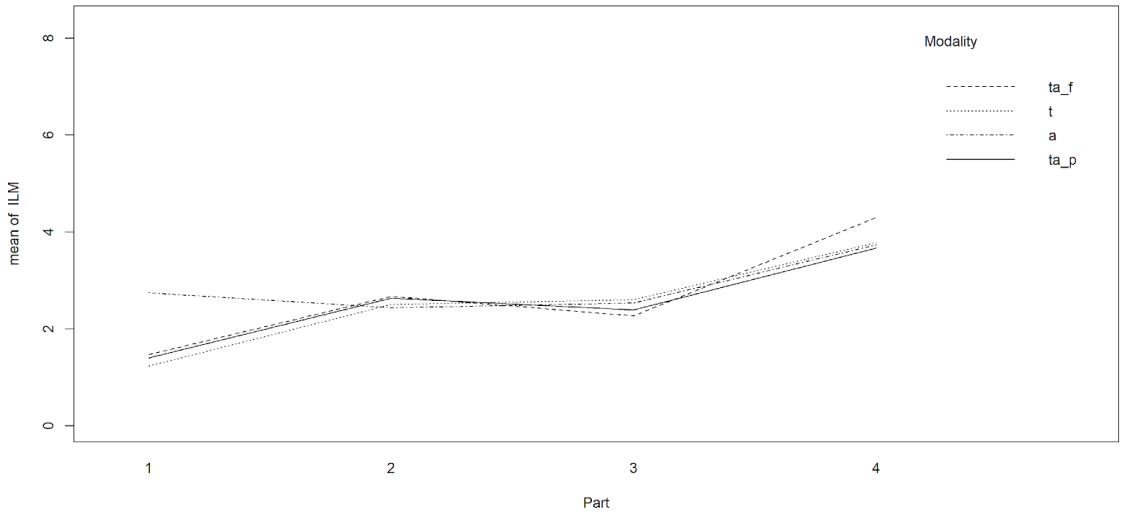


(g) Mental Effort (ME-Paas)

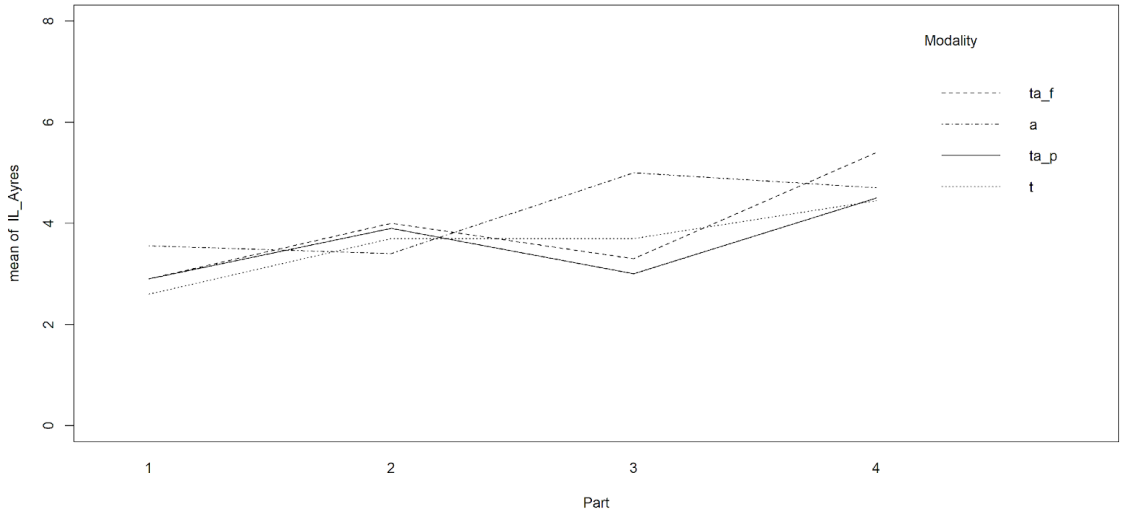


(h) EDA (Znormal SCR Mean)

Figure 4.4: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values for Test 2- mixed interaction effect of modality-redundancy X type of content on users' cognitive load.

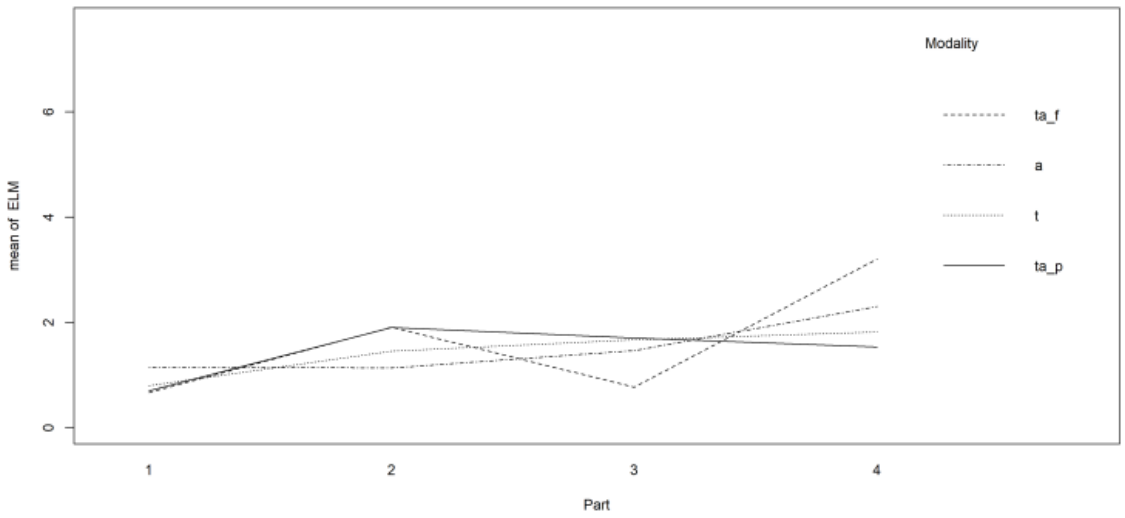


(a) Intrinsic Load Mean (ILM-Leppink)

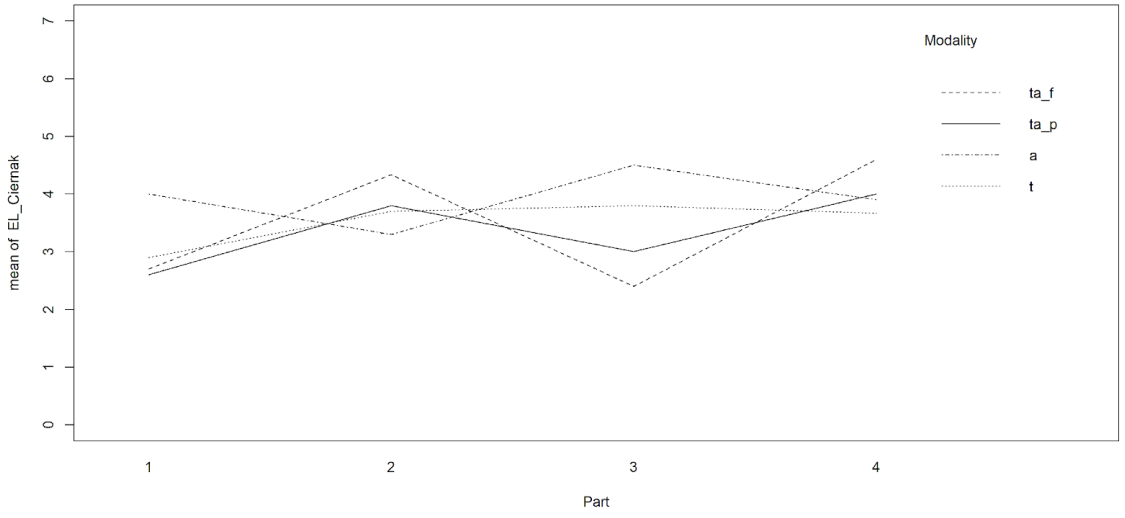


(b) Intrinsic Load (IL-Ayres)

Figure 4.5: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values.

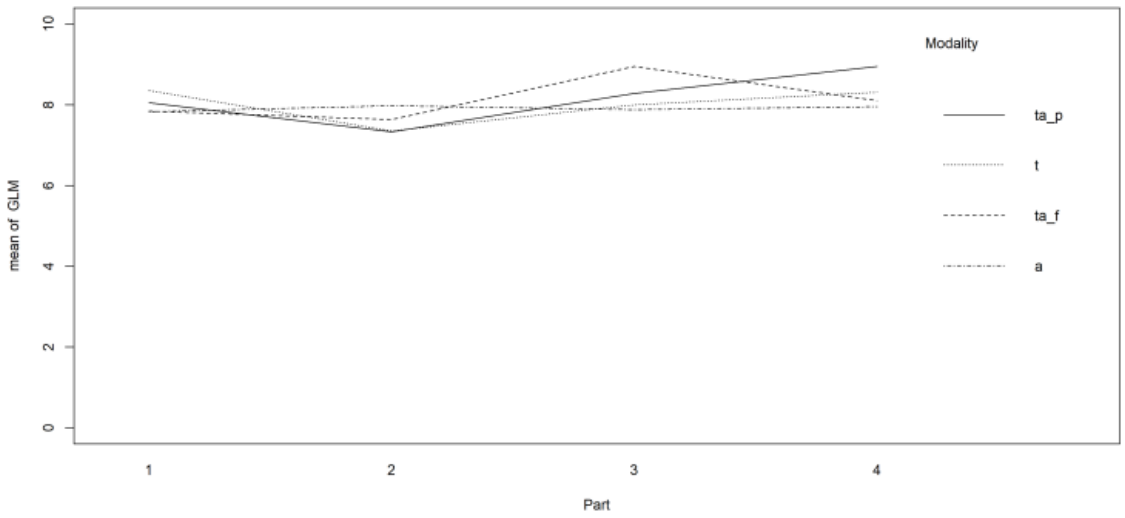


(c) Extrinsic Load Mean (ELM-Leppink)

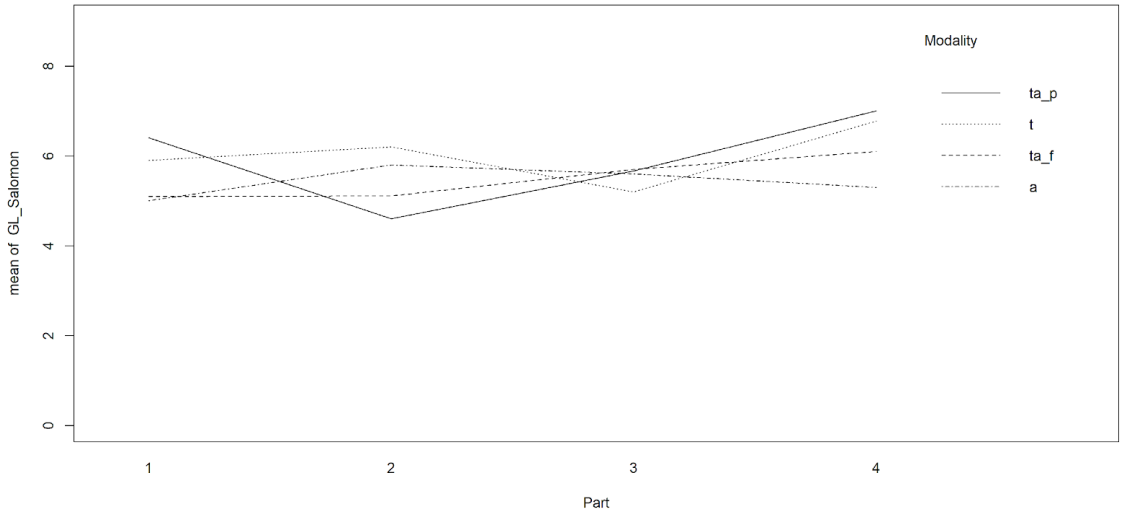


(d) Extrinsic Load (EL-Ciernak)

Figure 4.5: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values.

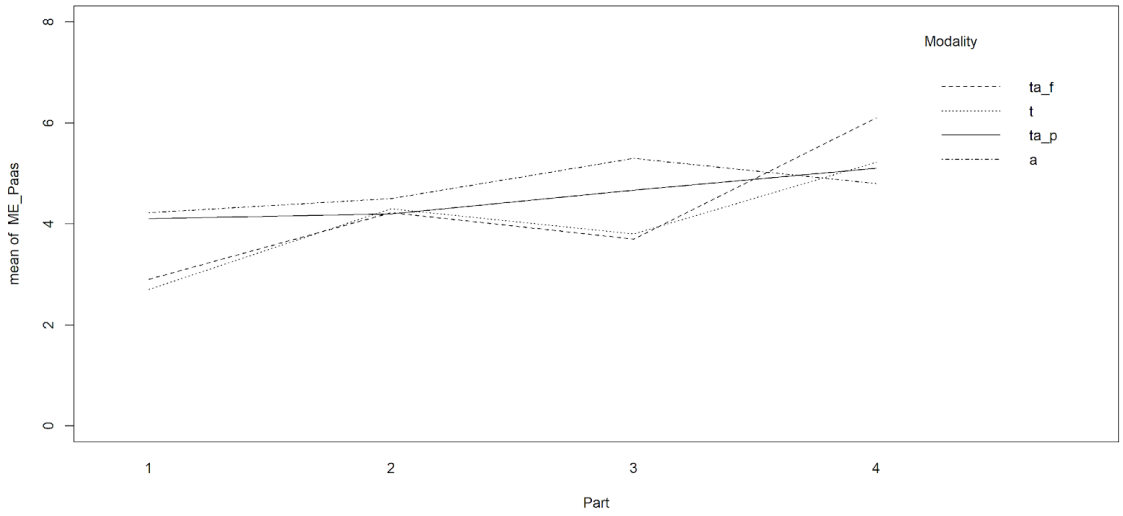


(e) Germane Load Mean (GLM-Leppink)

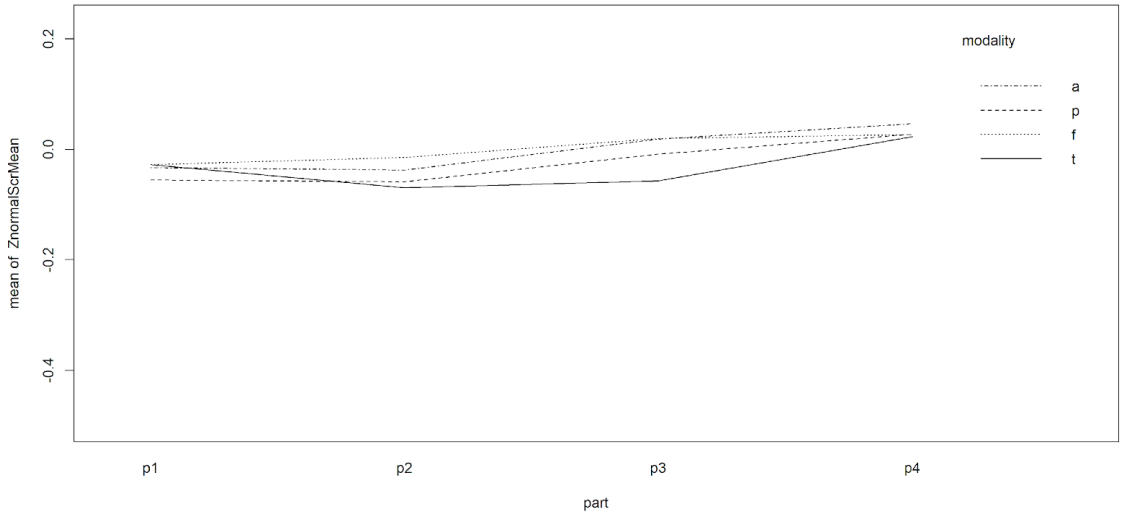


(f) Germane Load (GL-Saloman)

Figure 4.5: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values.

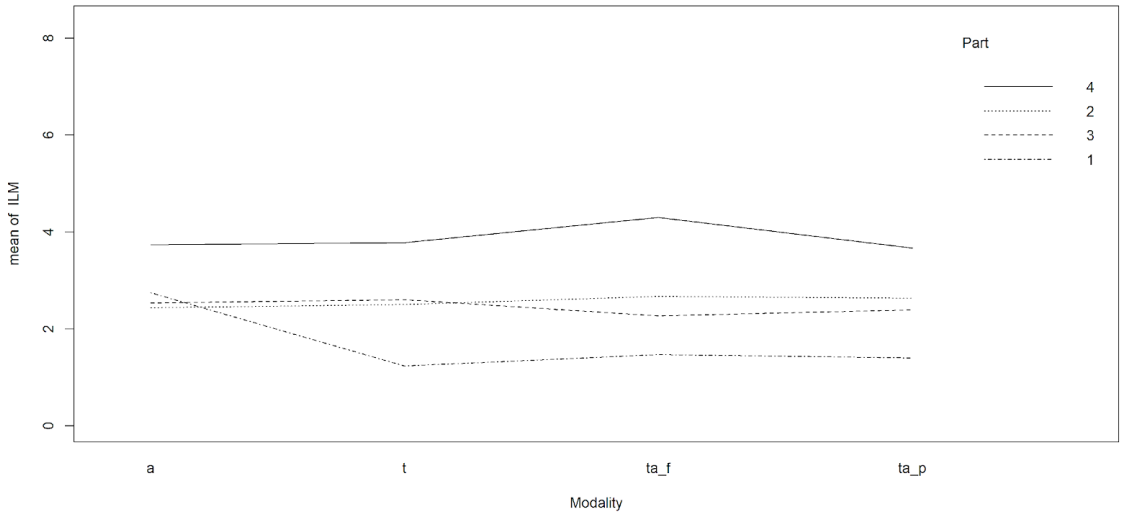


(g) Mental Effort (ME-Paas)

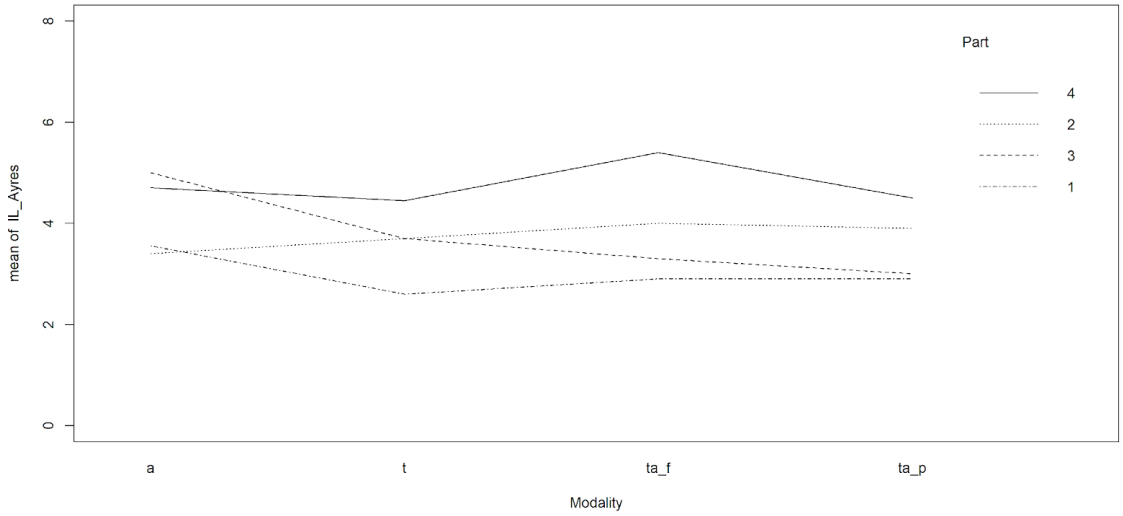


(h) EDA (Znormal SCR Mean)

Figure 4.5: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values.

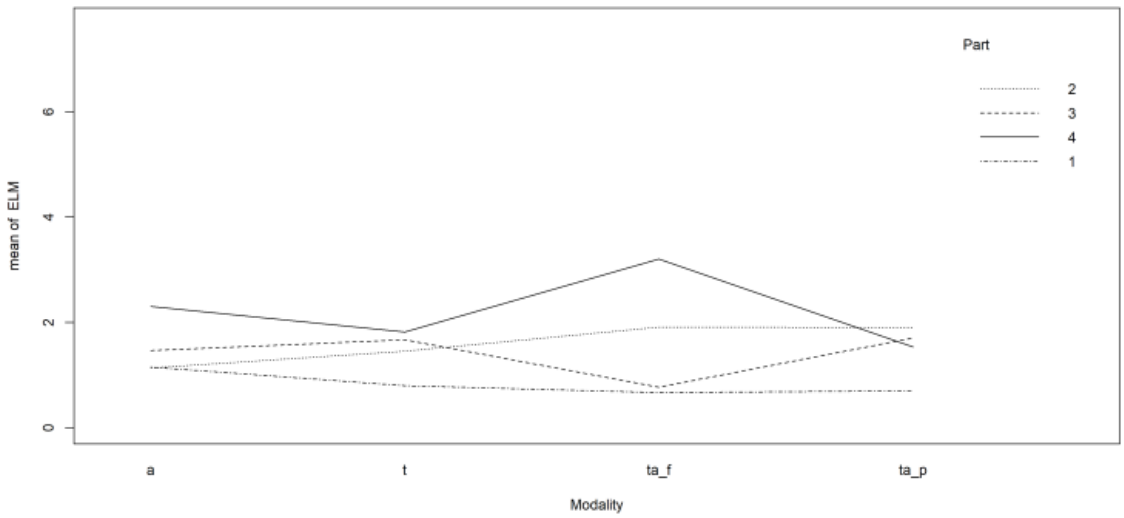


(a) Intrinsic Load Mean (ILM-Leppink)

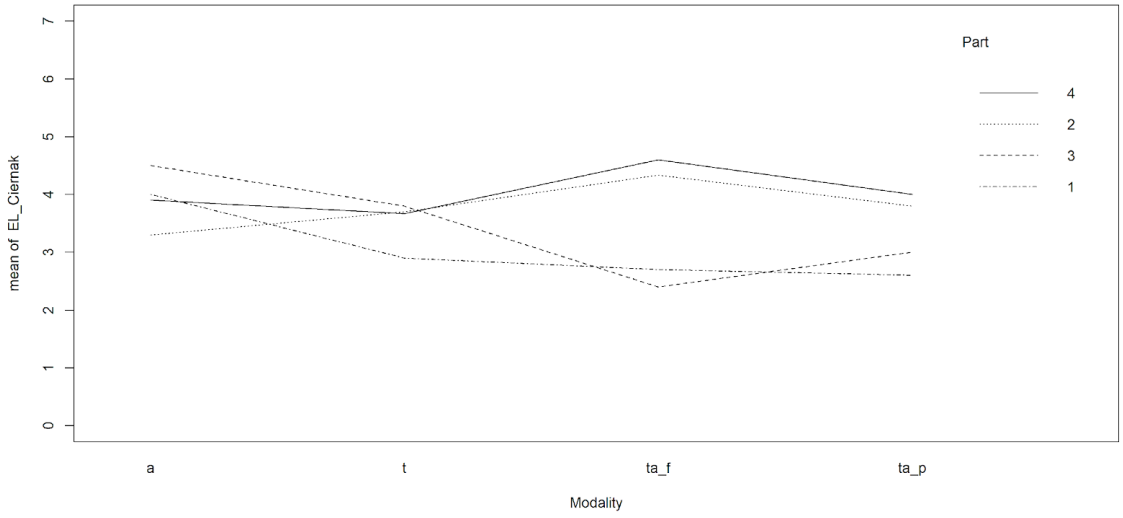


(b) Intrinsic Load (IL-Ayres)

Figure 4.6: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values.

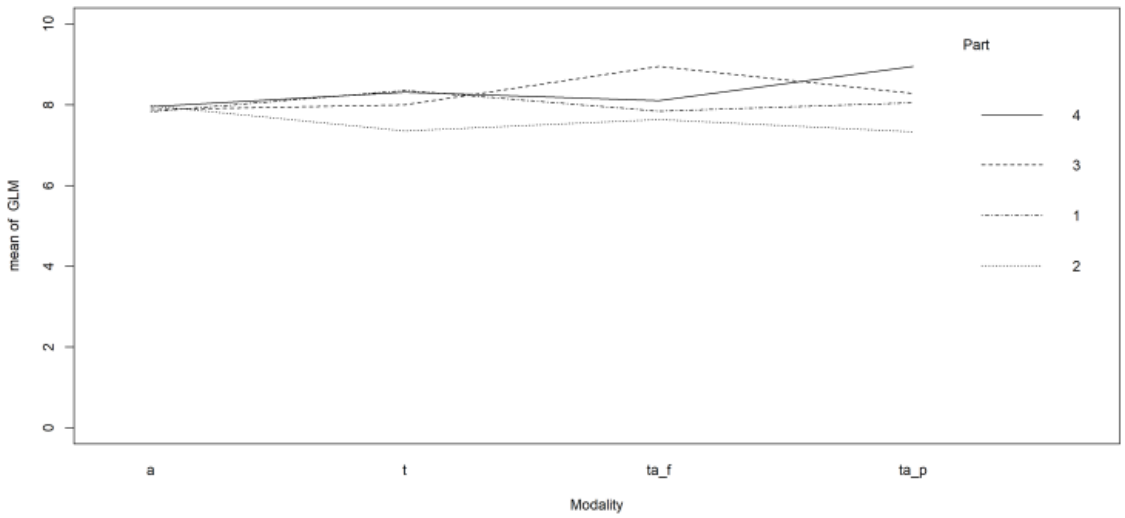


(c) Extrinsic Load Mean (ELM-Leppink)

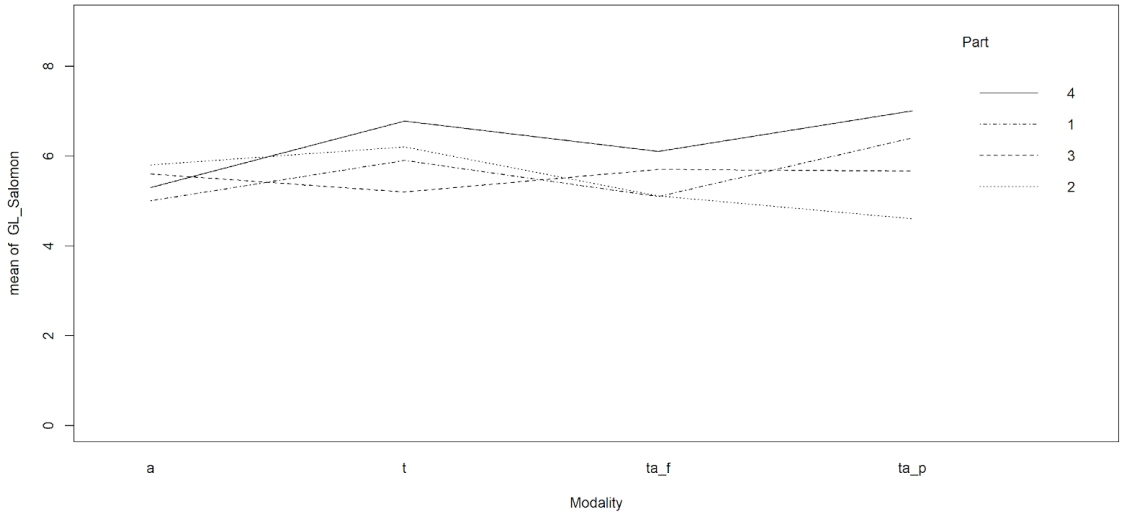


(d) Extrinsic Load (EL-Ciernak)

Figure 4.6: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values.

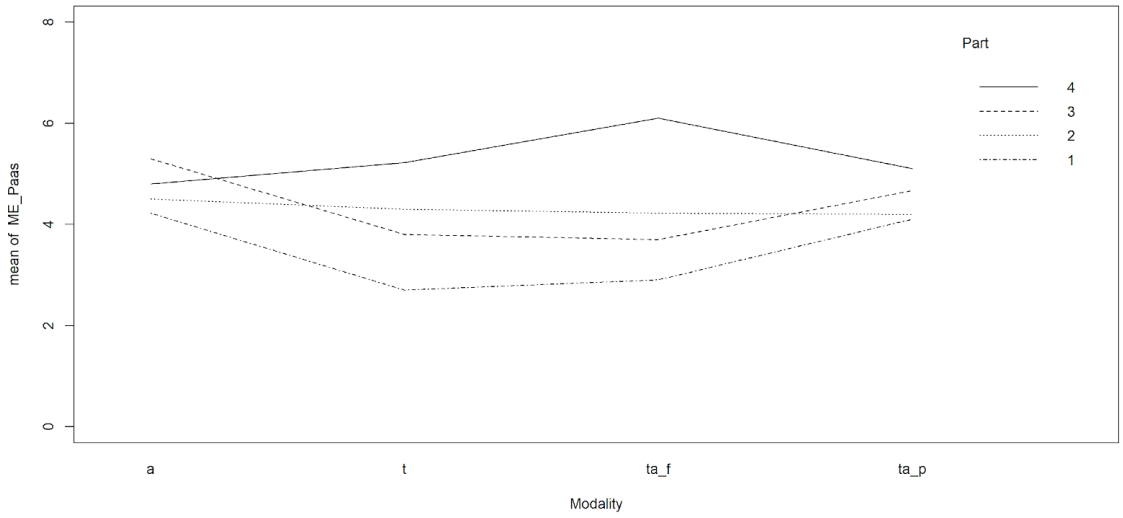


(e) Germane Load Mean (GLM-Leppink)

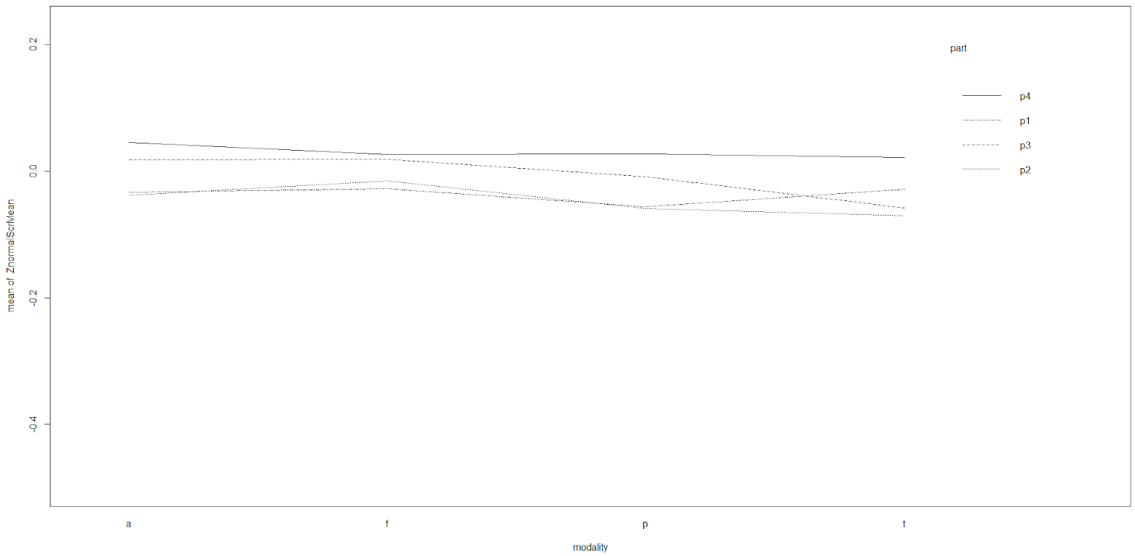


(f) Germane Load (GL-Saloman)

Figure 4.6: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values.

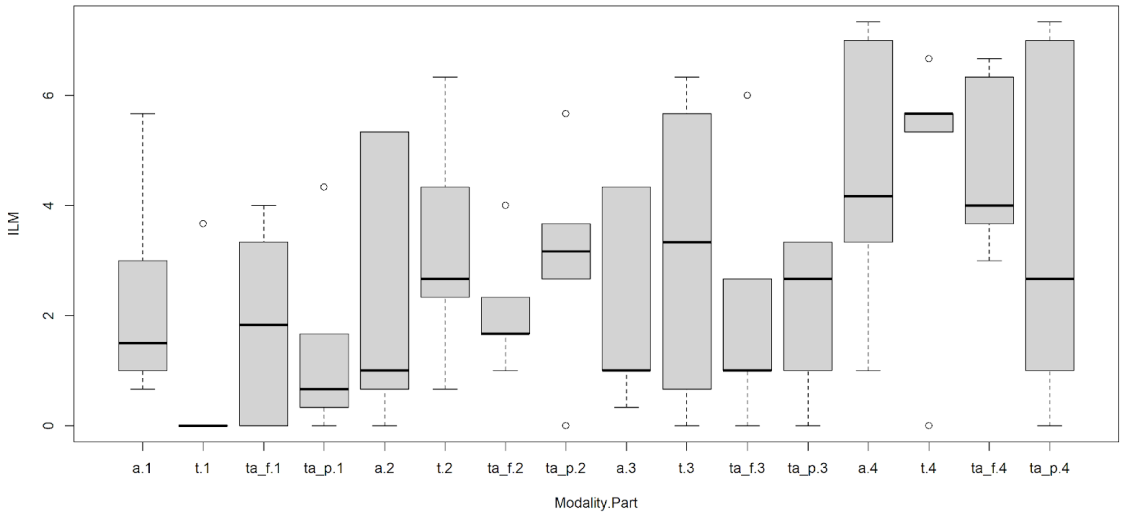


(g) Mental Effort (ME-Paas)

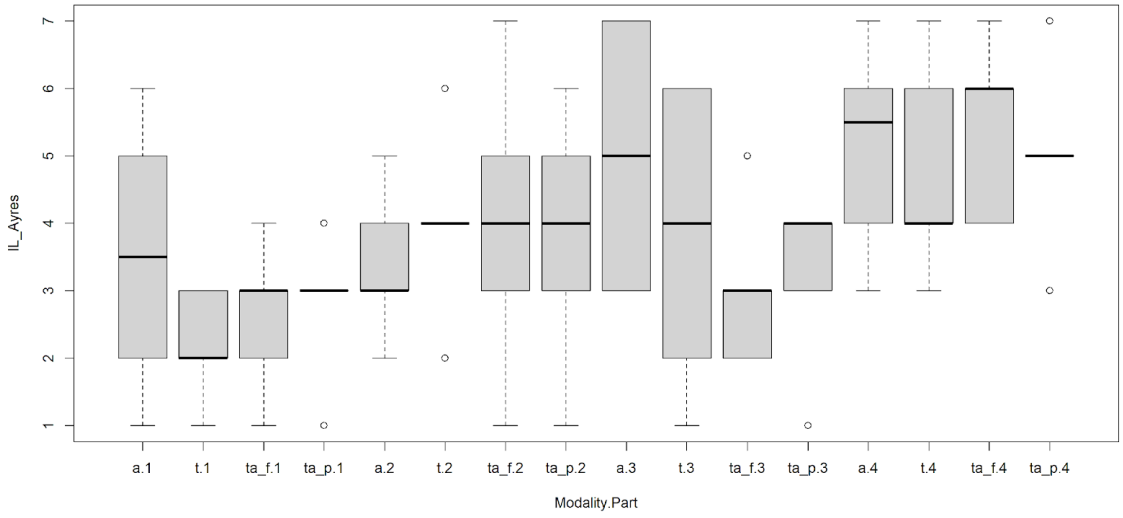


(h) EDA (Znormal SCR Mean)

Figure 4.6: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values.

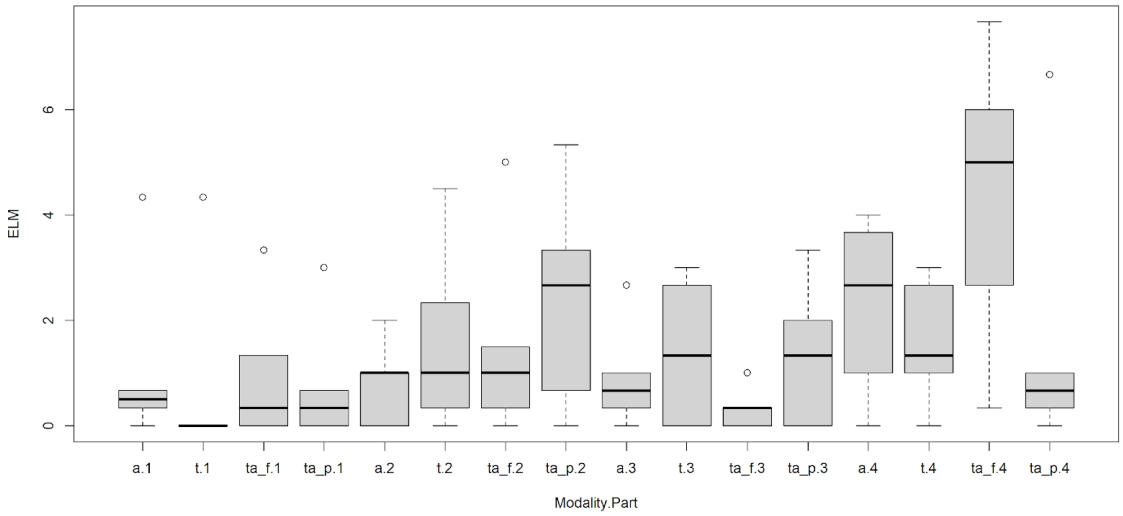


(a) Intrinsic Load Mean (ILM-Leppink)

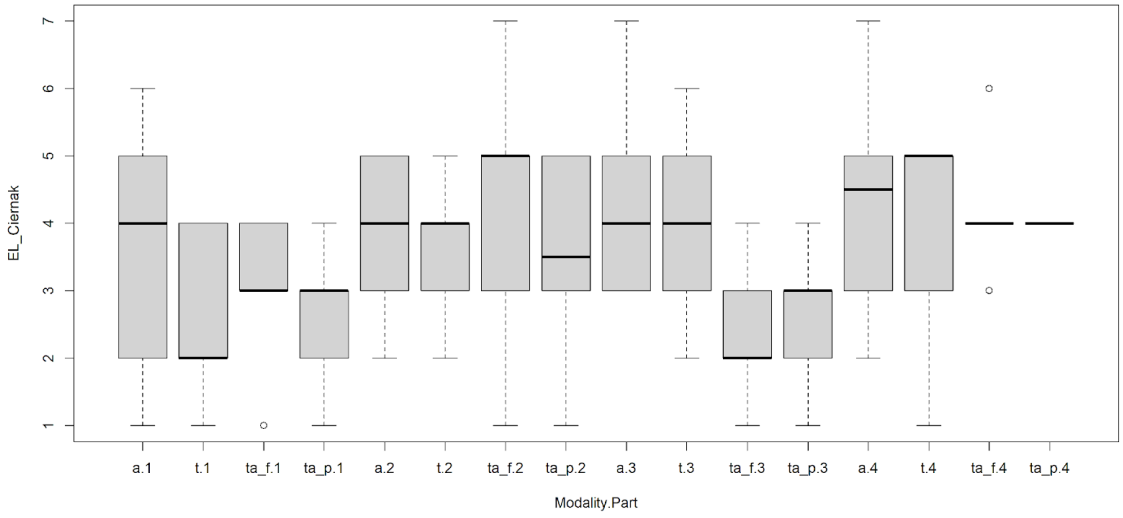


(b) Intrinsic Load (IL-Ayres)

Figure 4.7: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 1.

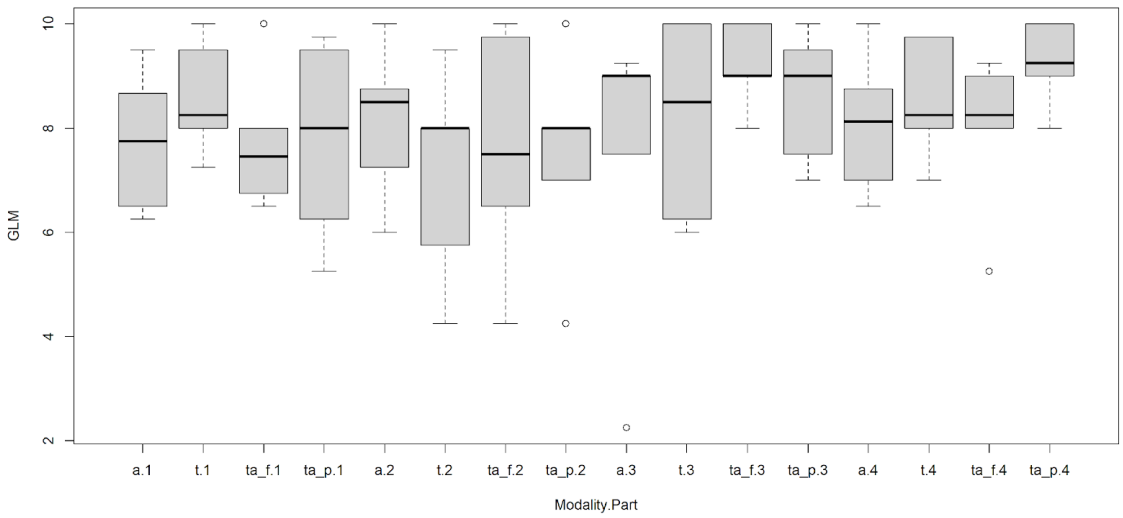


(c) Extrinsic Load Mean (ELM-Leppink)

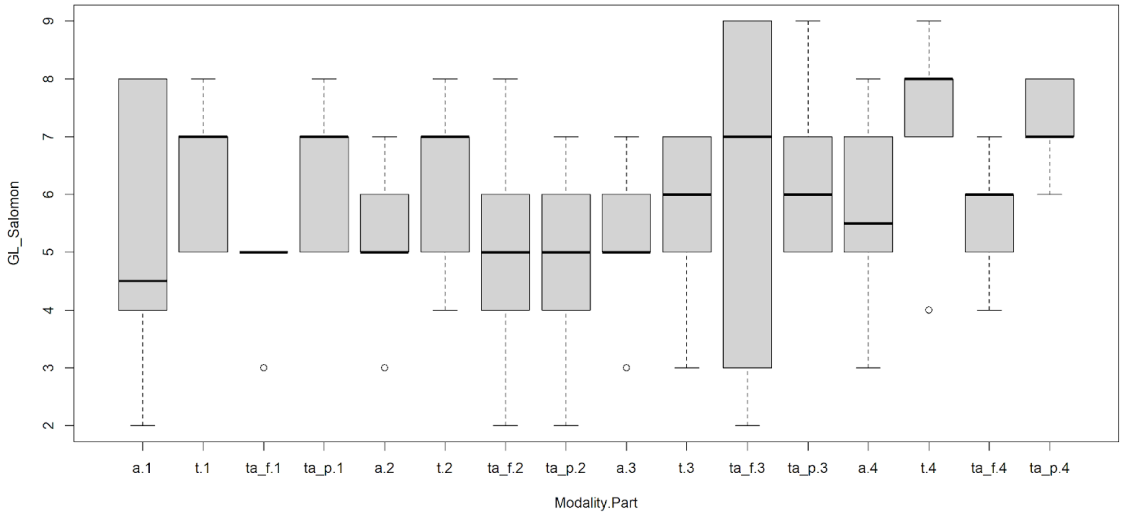


(d) Extrinsic Load (EL-Ciernak)

Figure 4.7: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 1.

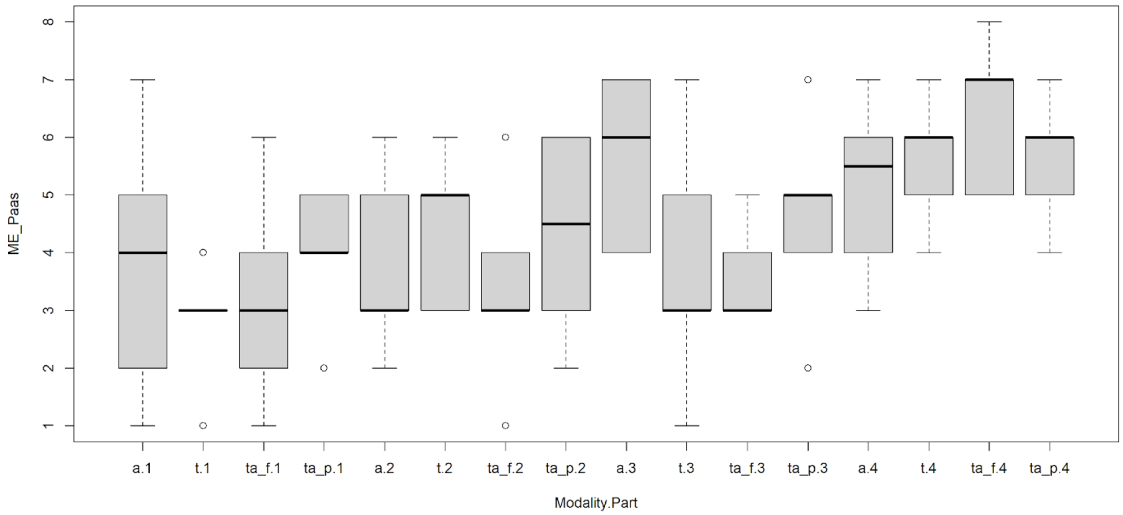


(e) Germane Load Mean (GLM-Leppink)

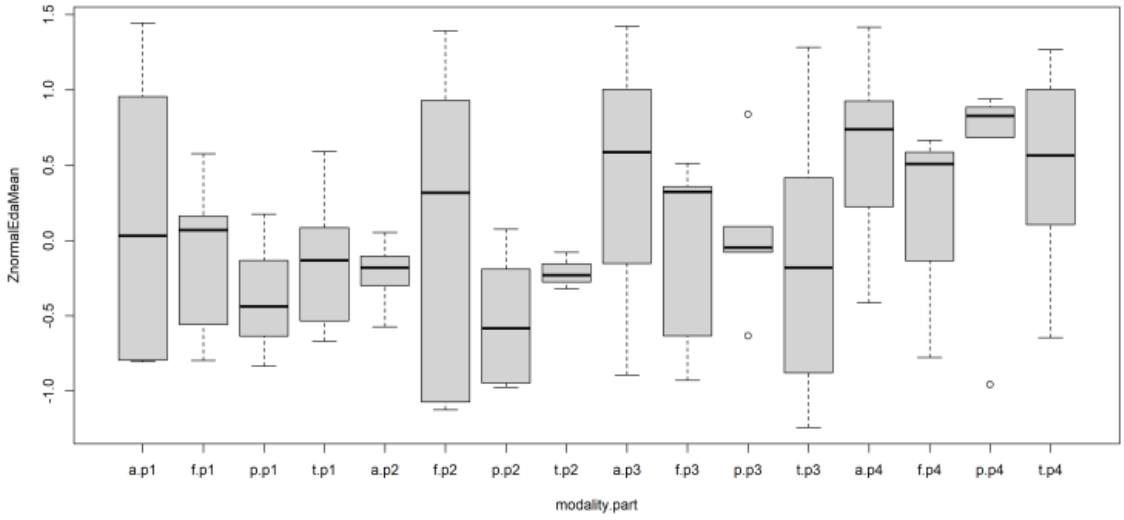


(f) Germane Load (GL-Saloman)

Figure 4.7: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 1.

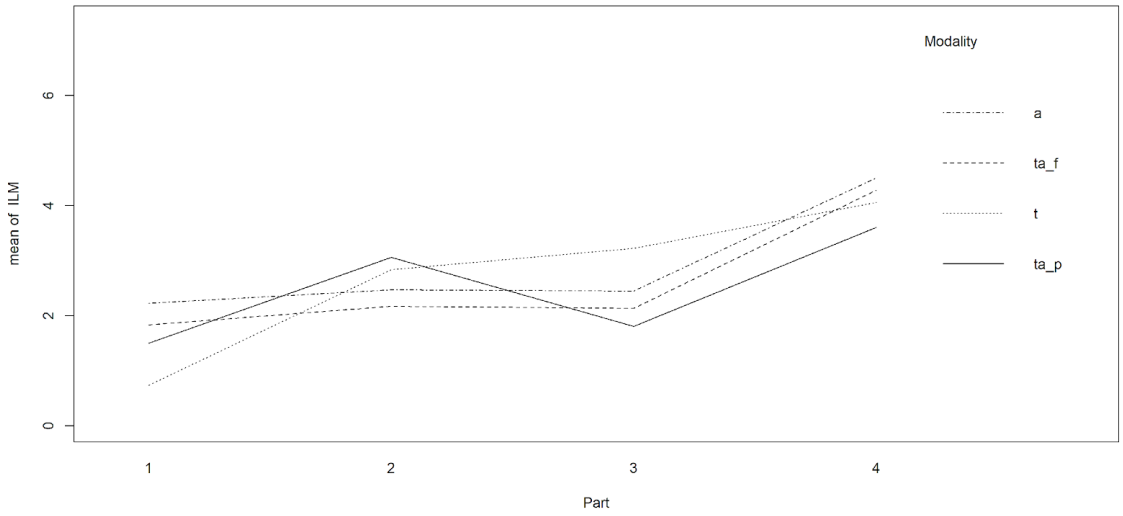


(g) Mental Effort (ME-Paas)

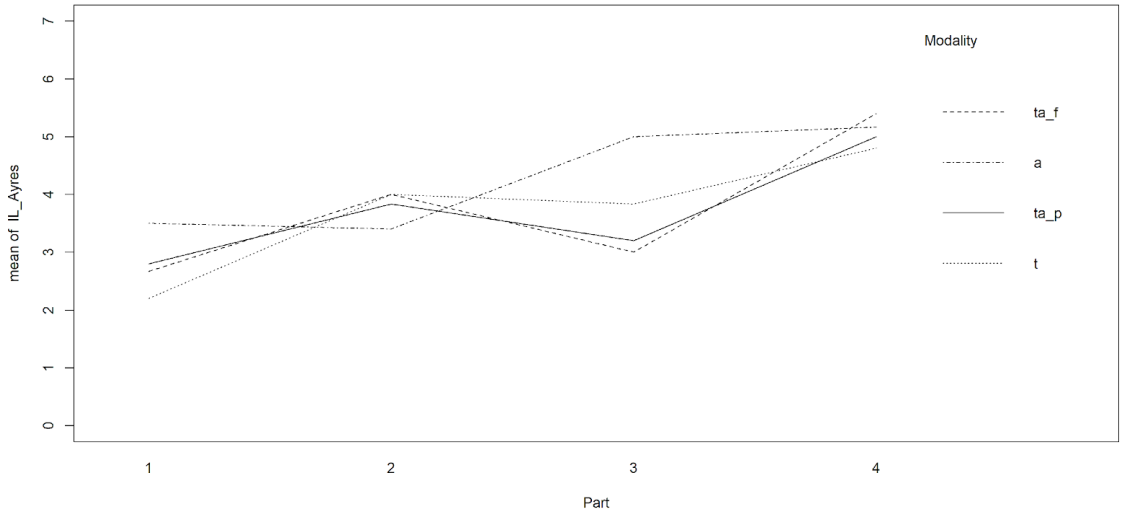


(h) EDA (Znormal SCR Mean)

Figure 4.7: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 1.

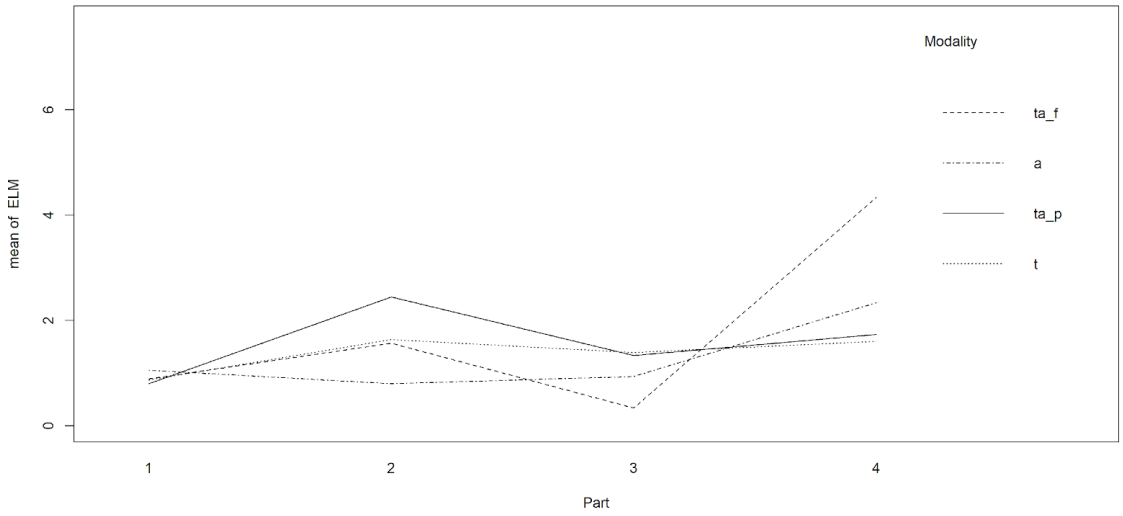


(a) Intrinsic Load Mean (ILM-Leppink)

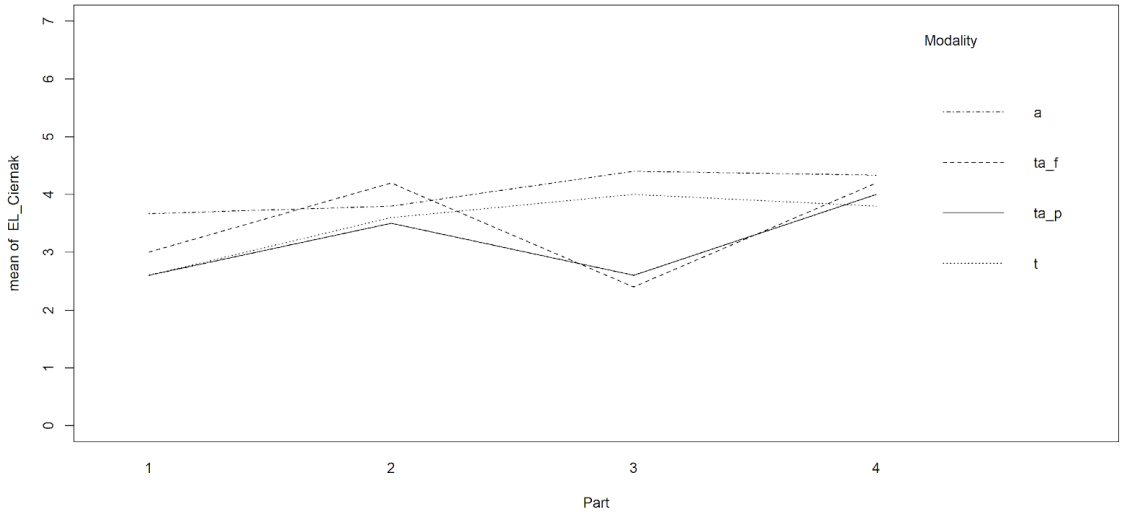


(b) Intrinsic Load (IL-Ayres)

Figure 4.8: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 1.

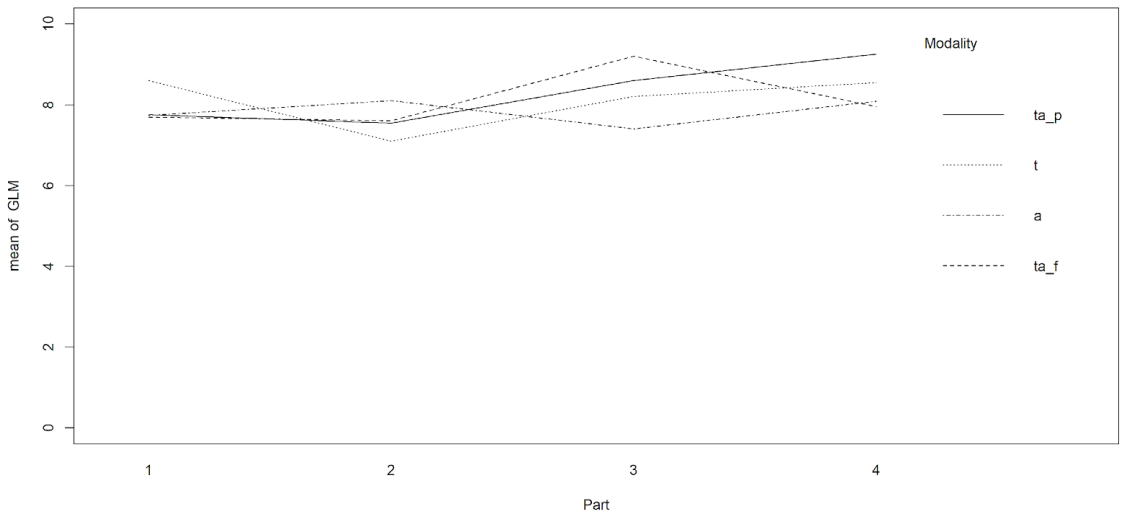


(c) Extrinsic Load Mean (ELM-Leppink)

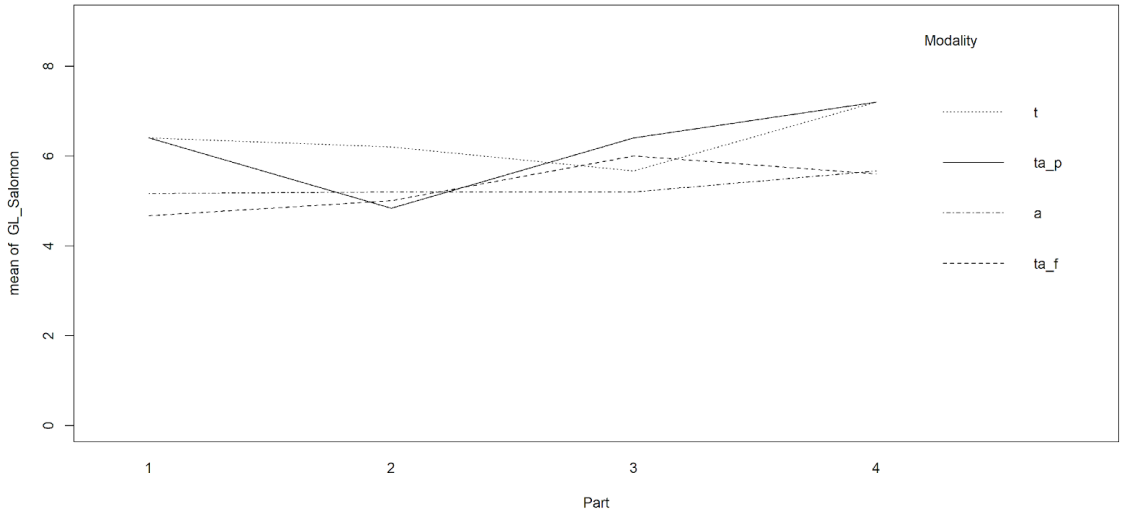


(d) Extrinsic Load (EL-Ciernak)

Figure 4.8: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 1.

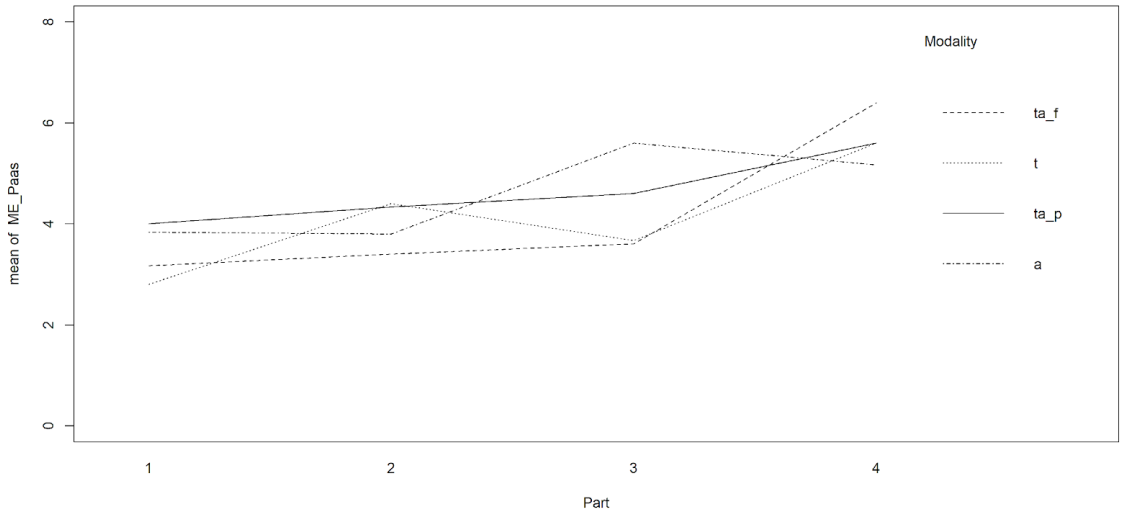


(e) Germane Load Mean (GLM-Leppink)

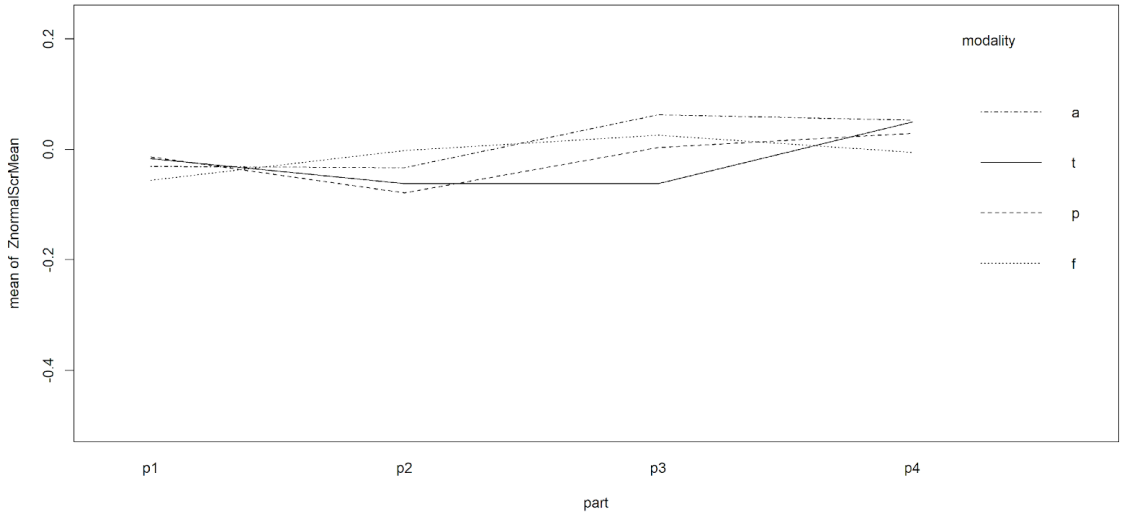


(f) Germane Load (GL-Saloman)

Figure 4.8: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 1.

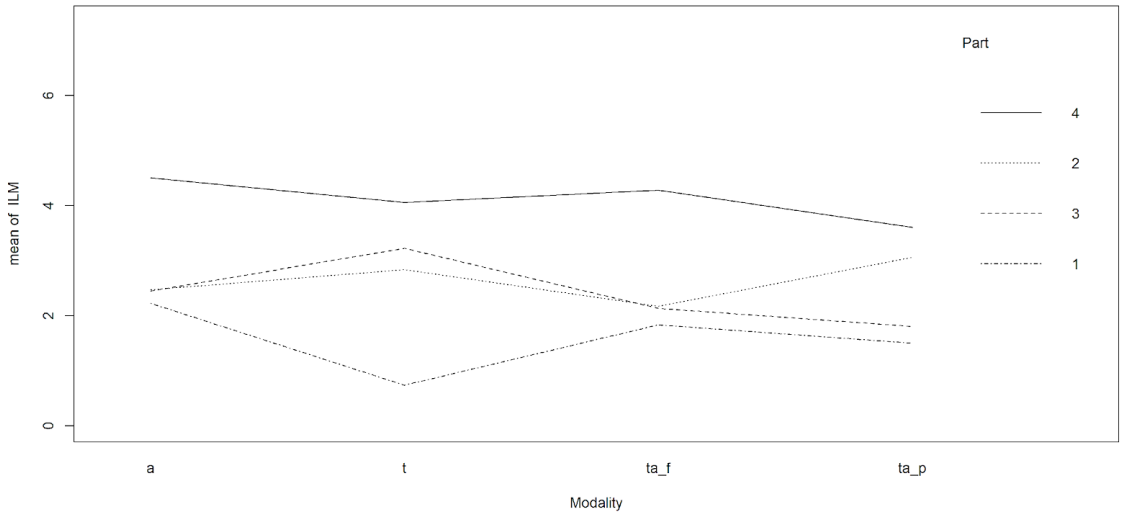


(g) Mental Effort (ME-Paas)

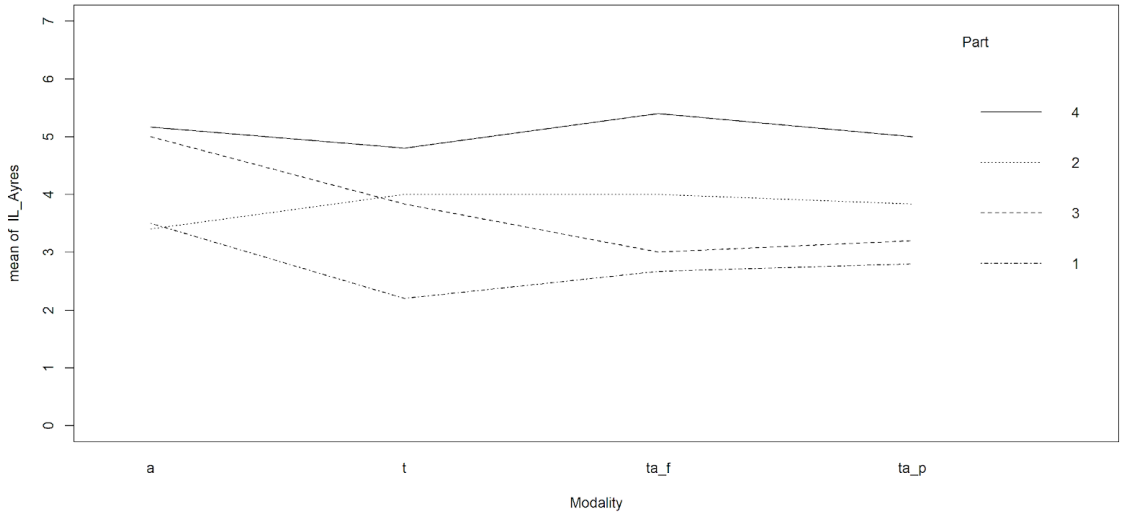


(h) EDA (Znormal SCR Mean)

Figure 4.8: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 1.

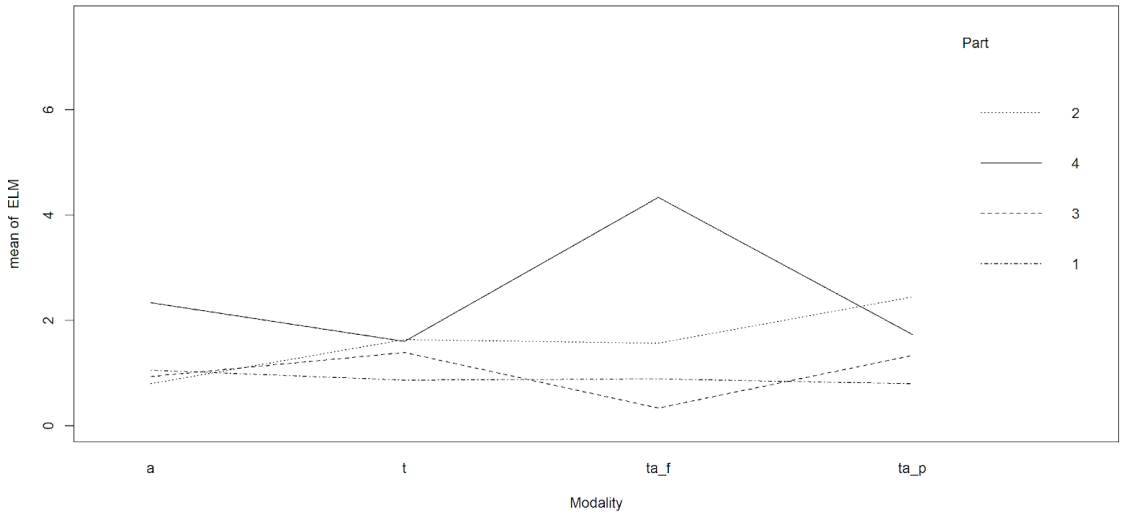


(a) Intrinsic Load Mean (ILM-Leppink)

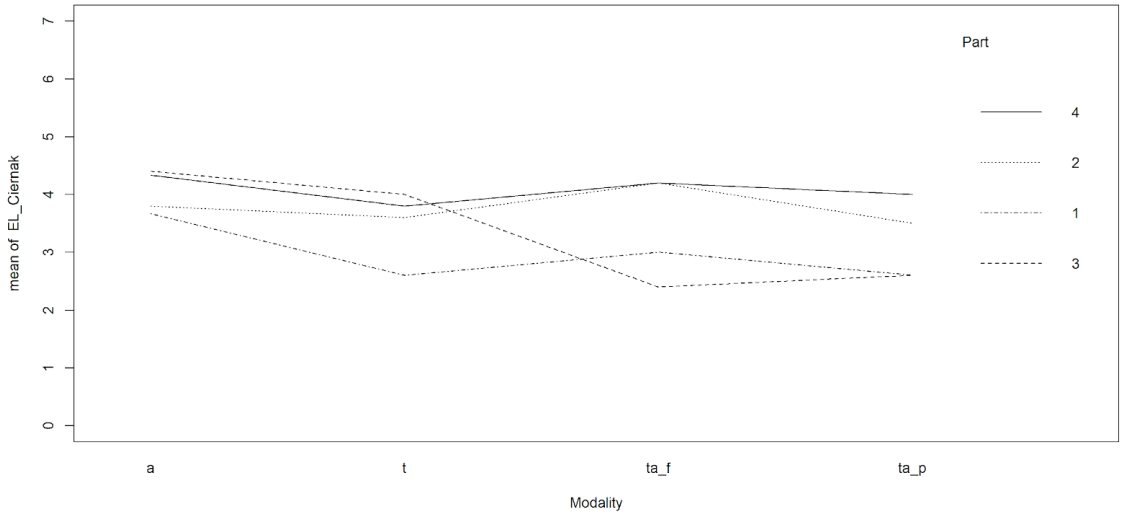


(b) Intrinsic Load (IL-Ayres)

Figure 4.9: The figures (a) to (h) illustrate interaction plots (type of content wise) for the subjective scales and EDA values of Group 1.

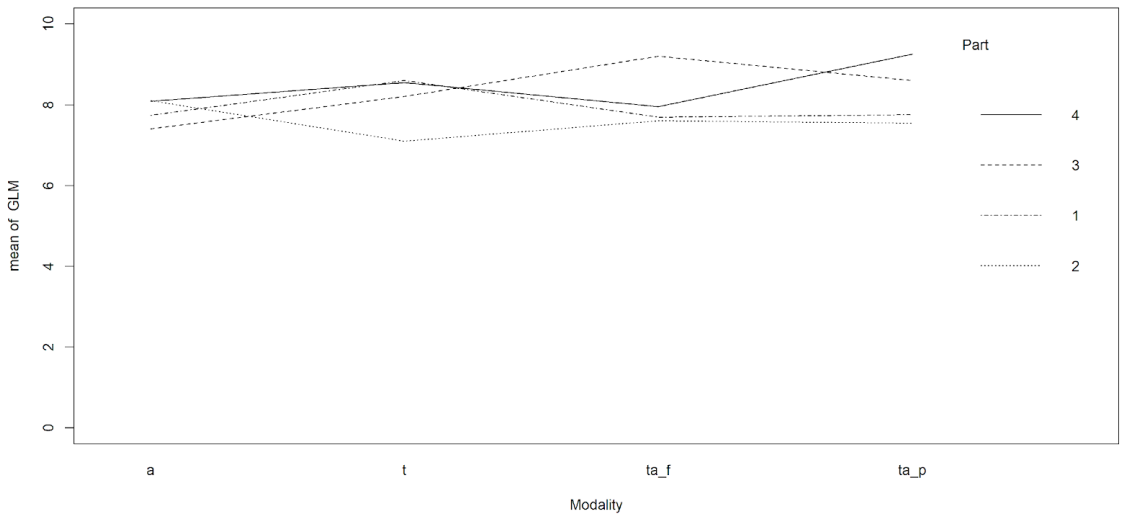


(c) Extrinsic Load Mean (ELM-Leppink)

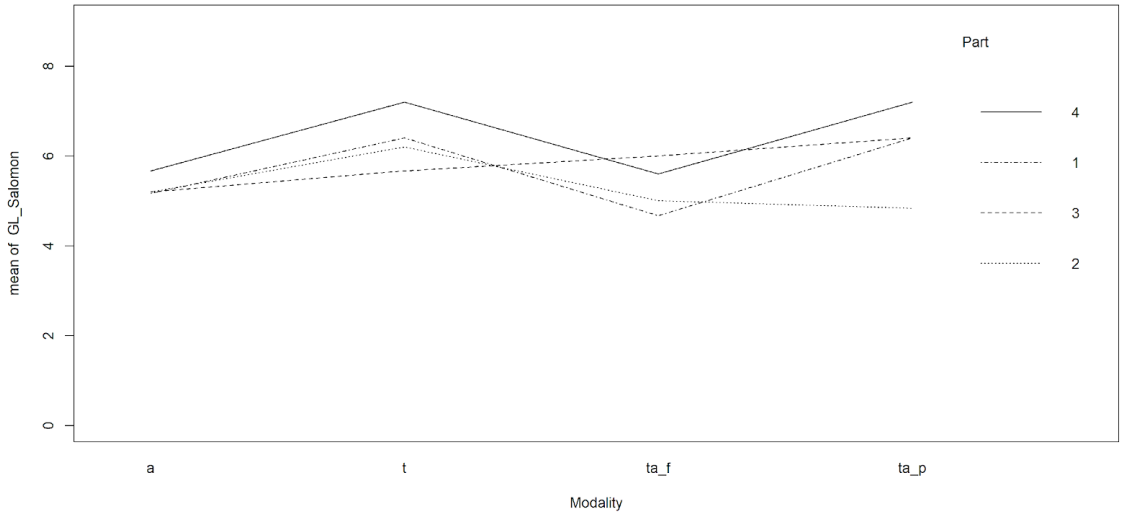


(d) Extrinsic Load (EL-Ciernak)

Figure 4.9: The figures (a) to (h) illustrate interaction plots (type of content wise) for the subjective scales and EDA values of Group 1.

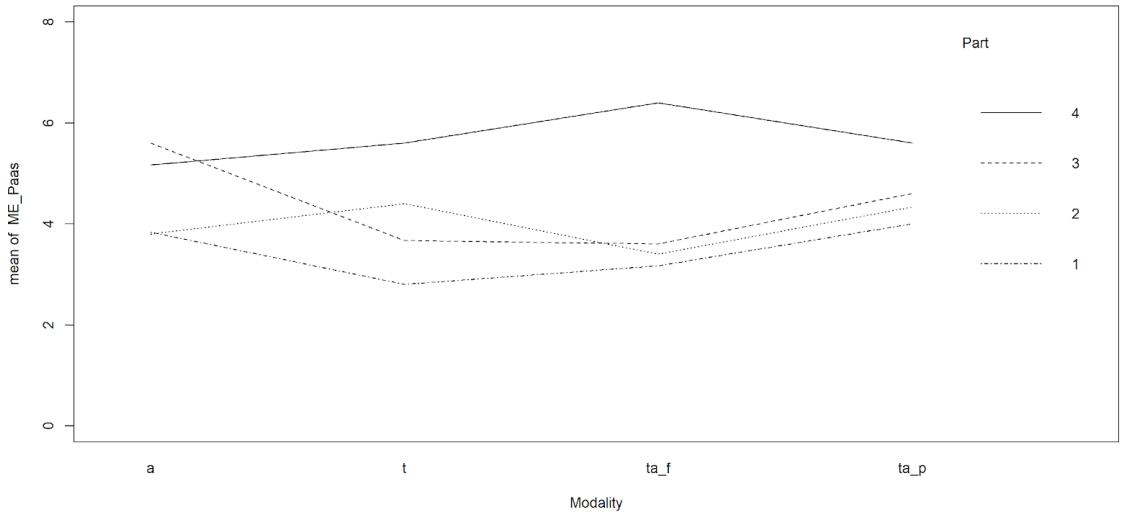


(e) Germane Load Mean (GLM-Leppink)

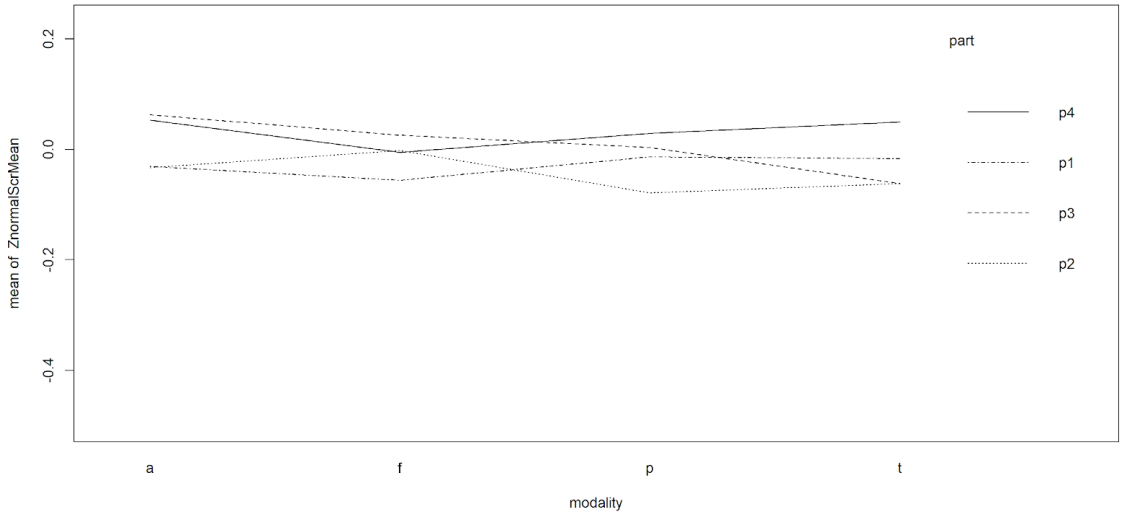


(f) Germane Load (GL-Saloman)

Figure 4.9: The figures (a) to (h) illustrate interaction plots (type of content wise) for the subjective scales and EDA values of Group 1.

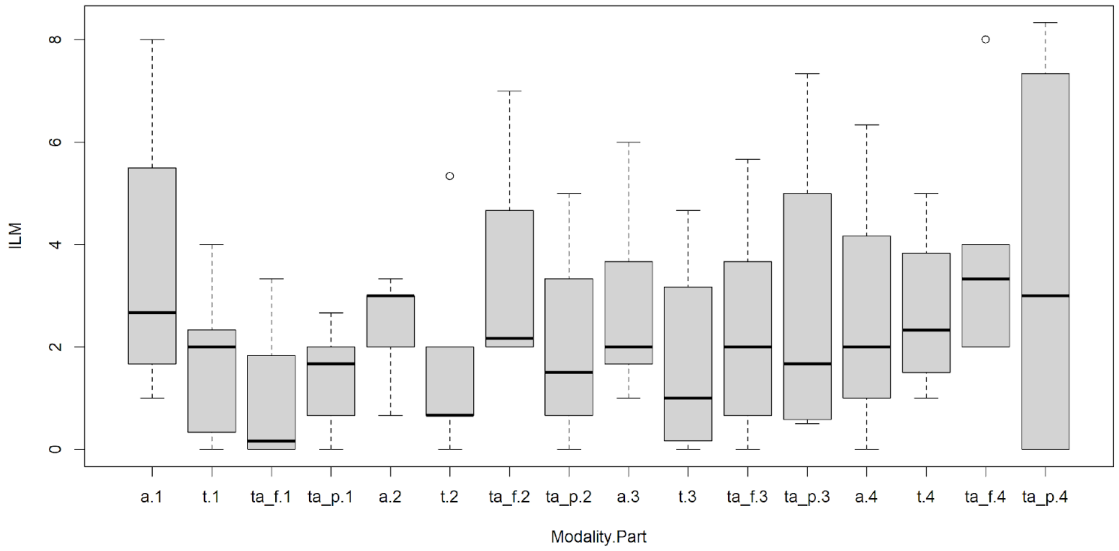


(g) Mental Effort (ME-Paas)

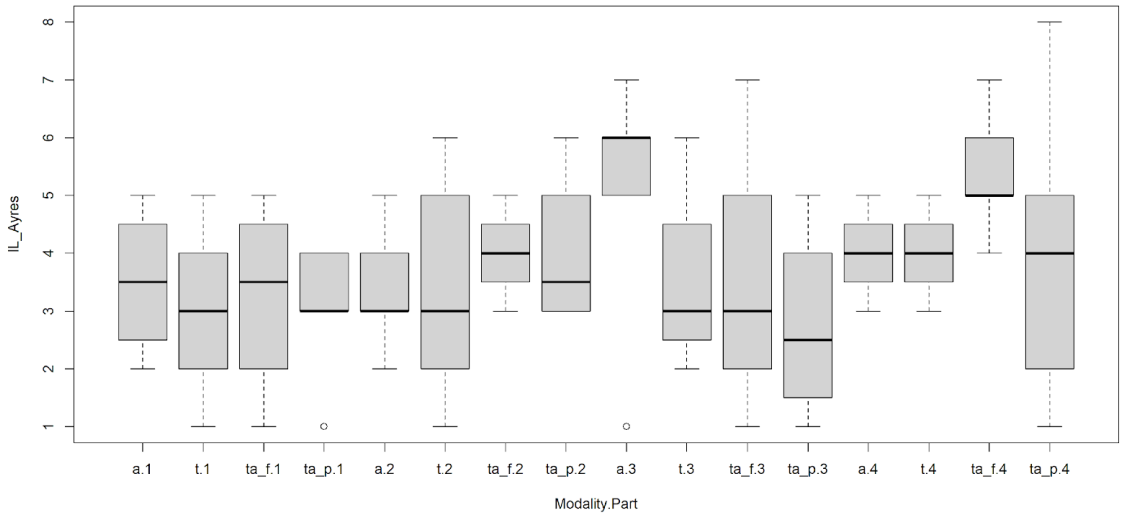


(h) EDA (Znormal SCR Mean)

Figure 4.9: The figures (a) to (h) illustrate interaction plots (type of content wise) for the subjective scales and EDA values of Group 1.

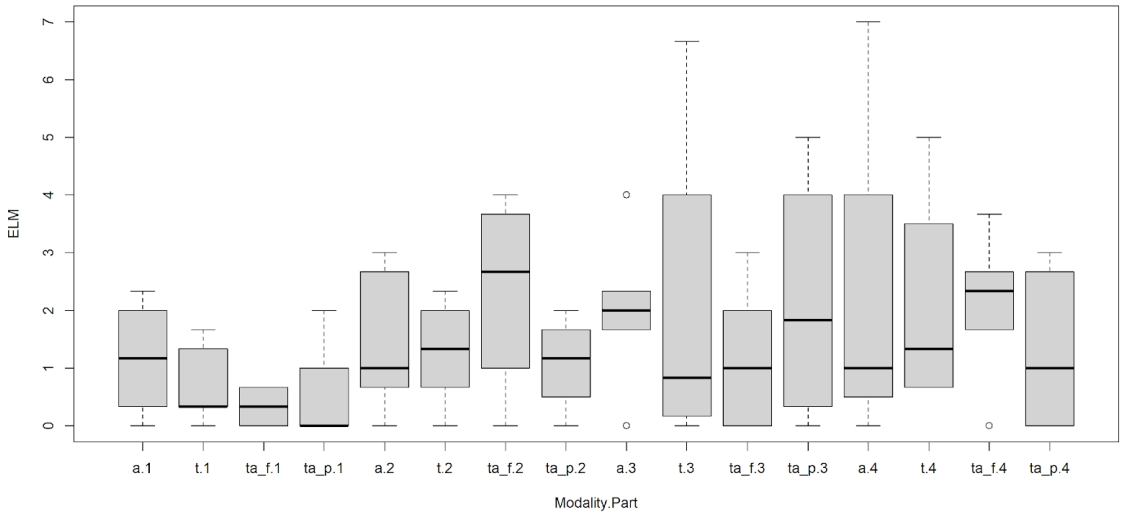


(a) Intrinsic Load Mean (ILM-Leppink)

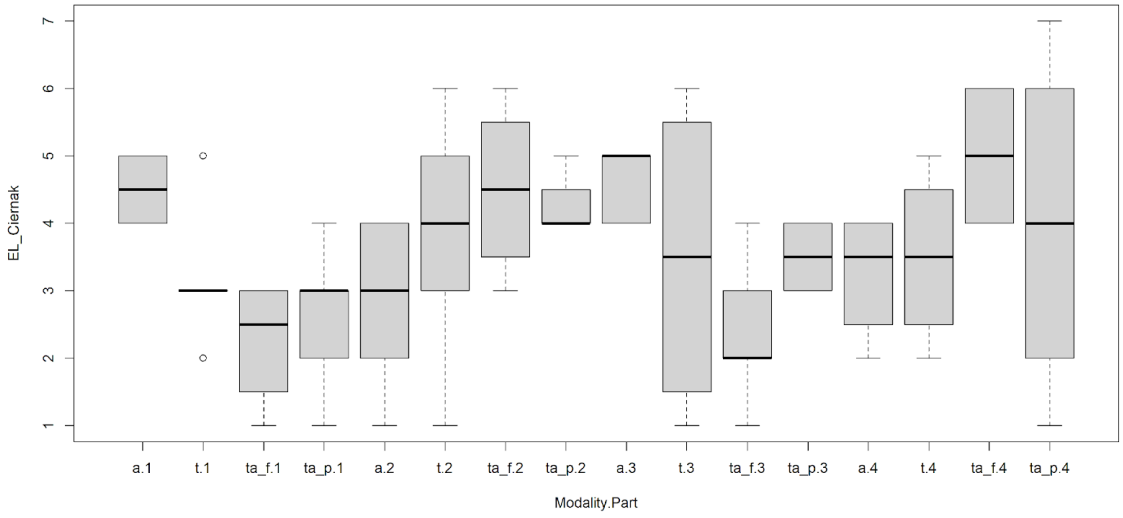


(b) Intrinsic Load (IL-Ayres)

Figure 4.10: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 2.

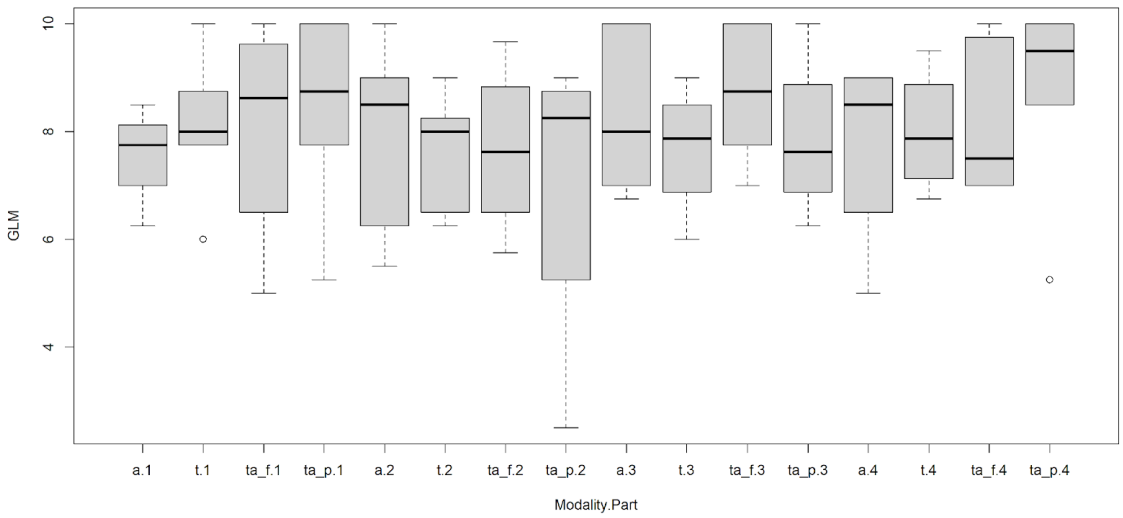


(c) Extrinsic Load Mean (ELM-Leppink)

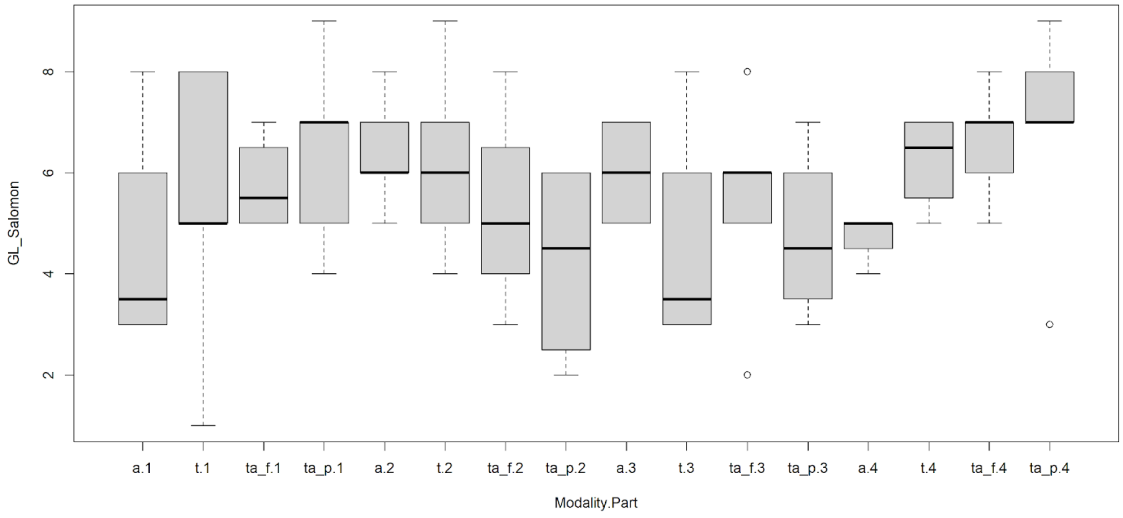


(d) Extrinsic Load (EL-Ciernak)

Figure 4.10: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 2.

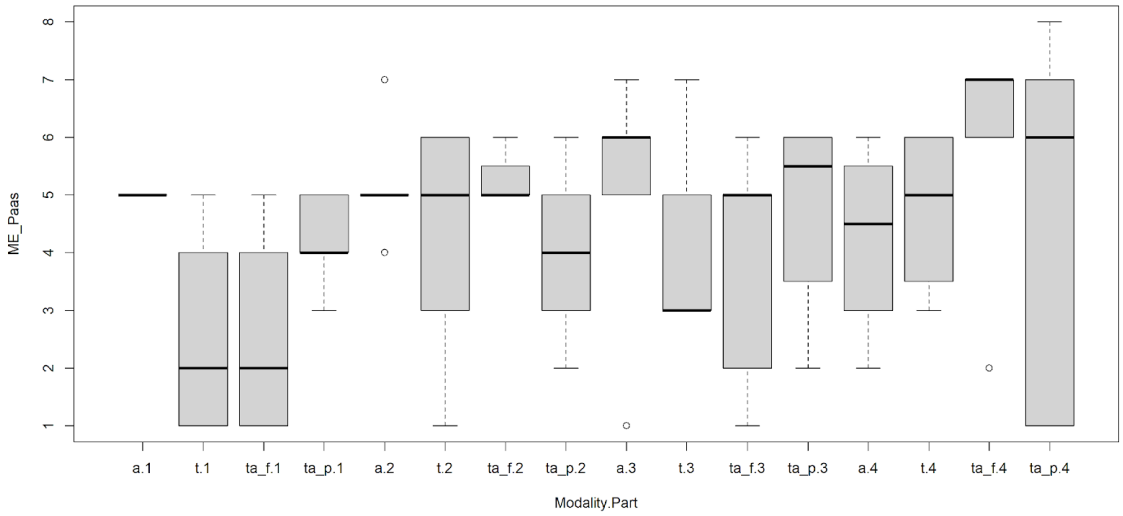


(e) Germane Load Mean (GLM-Leppink)

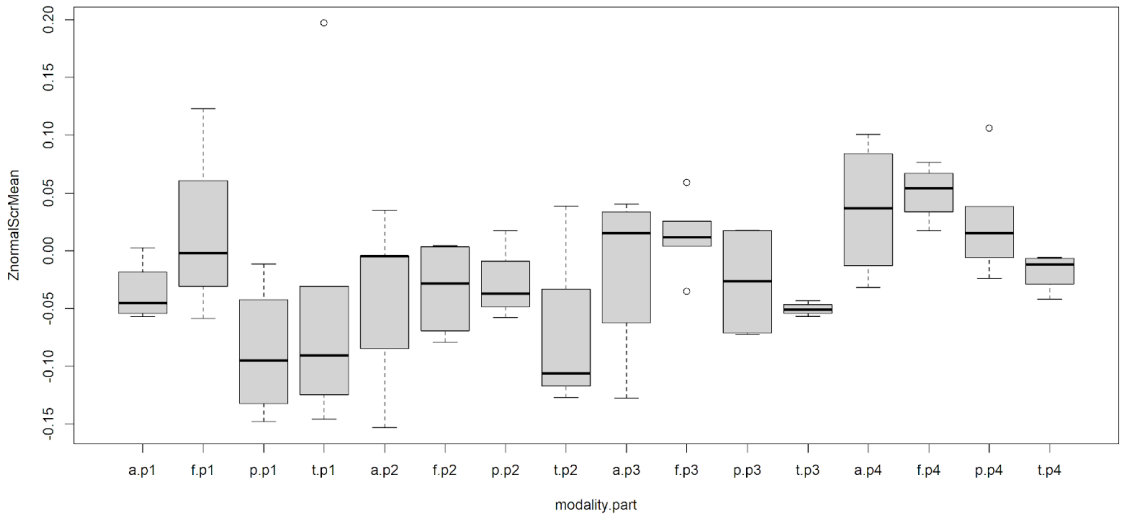


(f) Germane Load (GL-Saloman)

Figure 4.10: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 2.

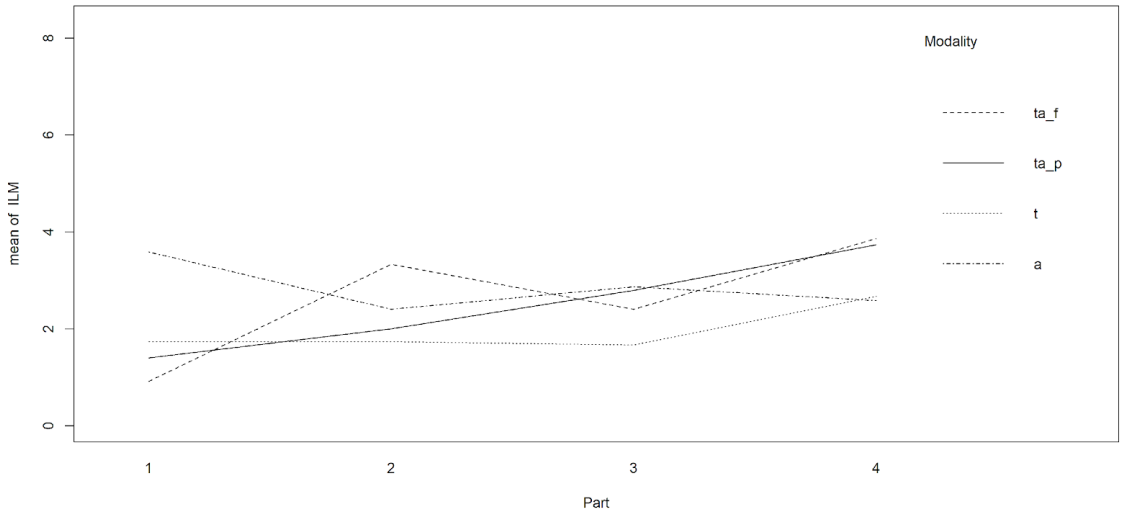


(g) Mental Effort (ME-Paas)

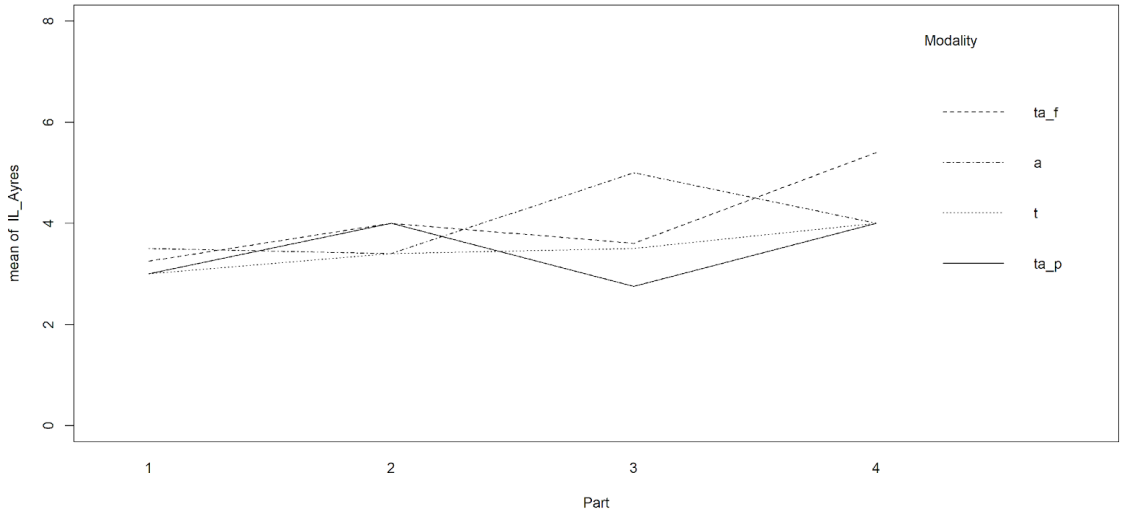


(h) EDA (Znormal SCR Mean)

Figure 4.10: The figures (a) to (h) illustrate the box plots for the subjective scales and EDA values of Group 2.

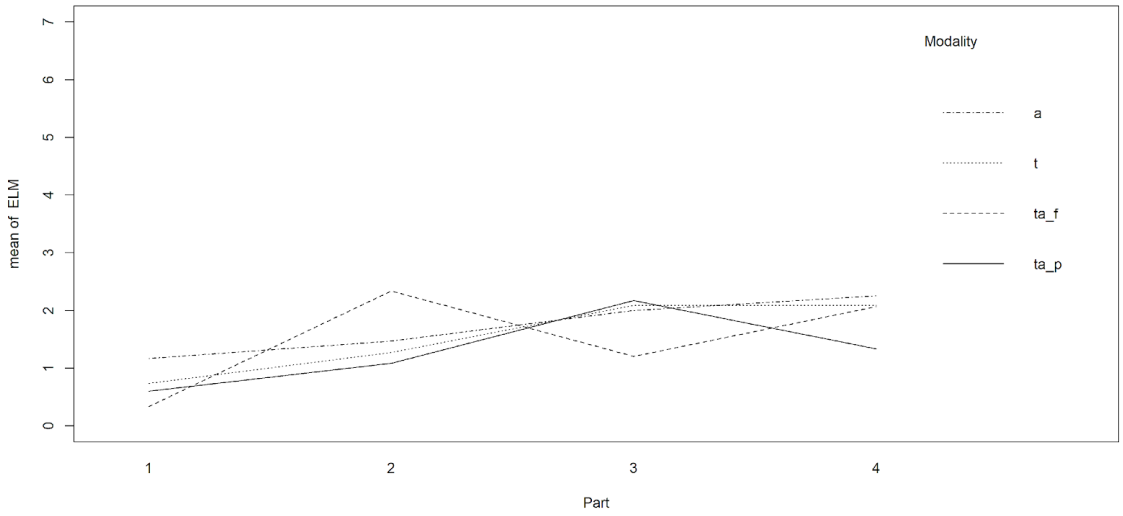


(a) Intrinsic Load Mean (ILM-Leppink)

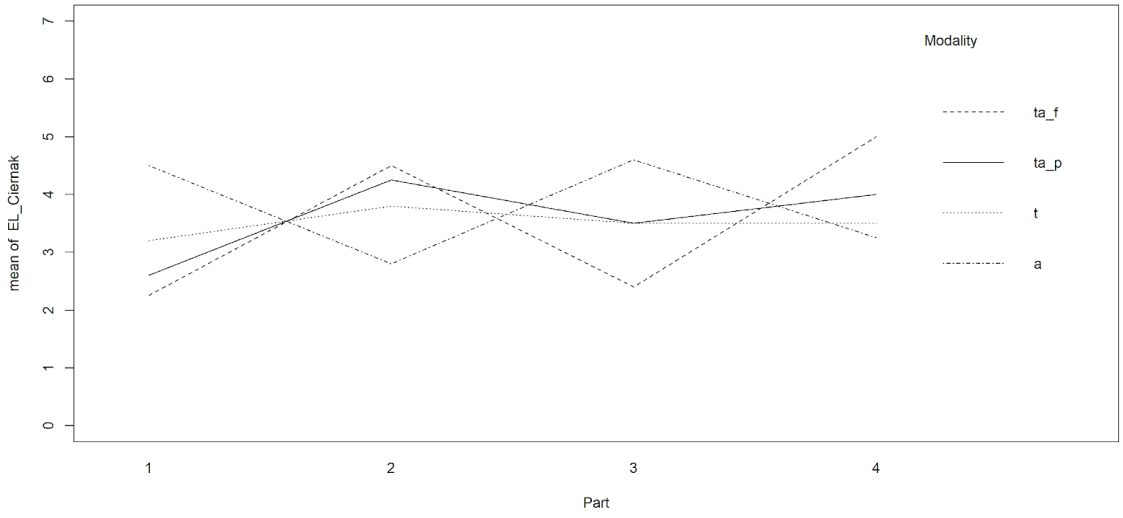


(b) Intrinsic Load (IL-Ayres)

Figure 4.11: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 2.

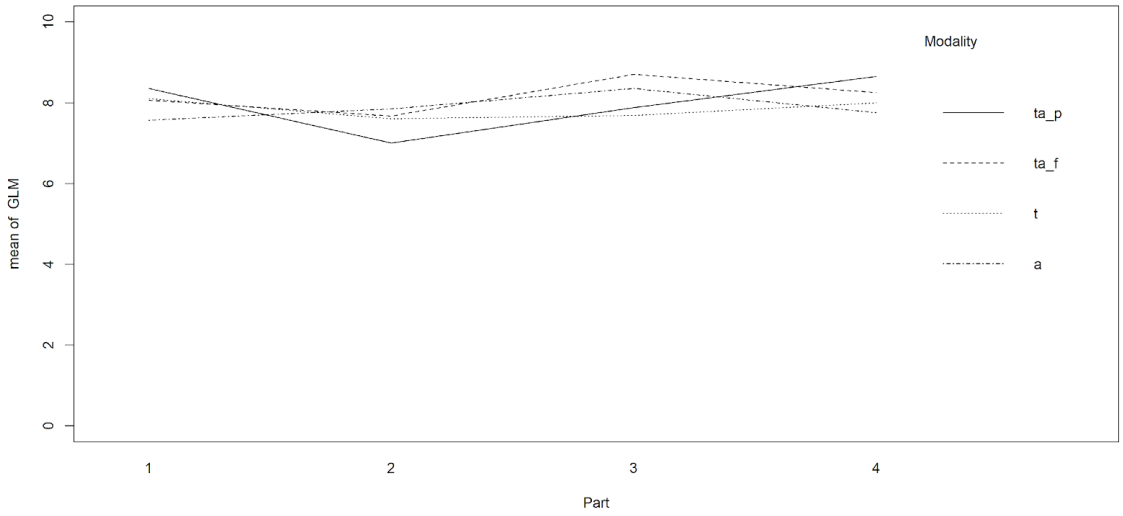


(c) Extrinsic Load Mean (ELM-Leppink)

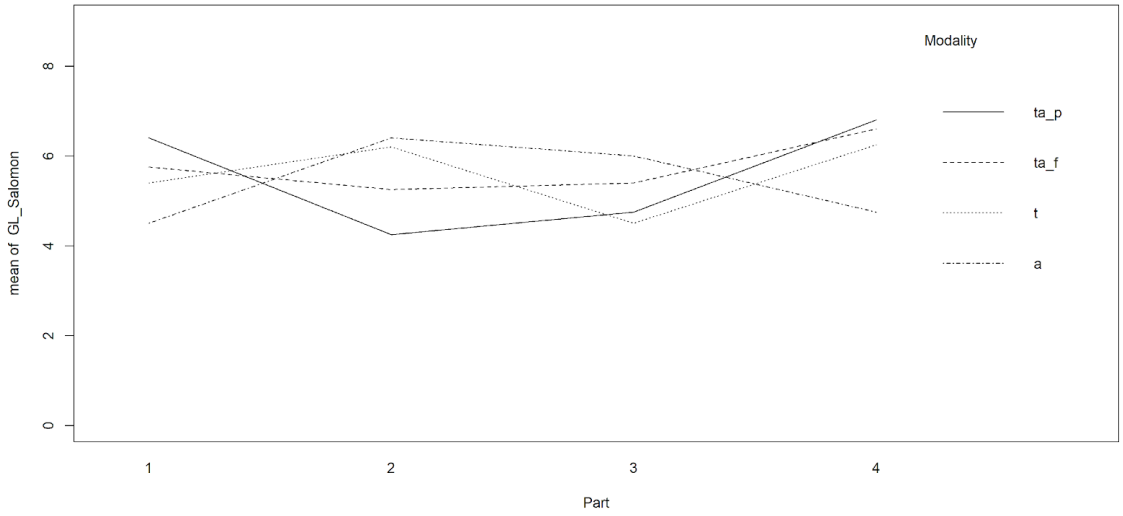


(d) Extrinsic Load (EL-Ciernak)

Figure 4.11: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 2.

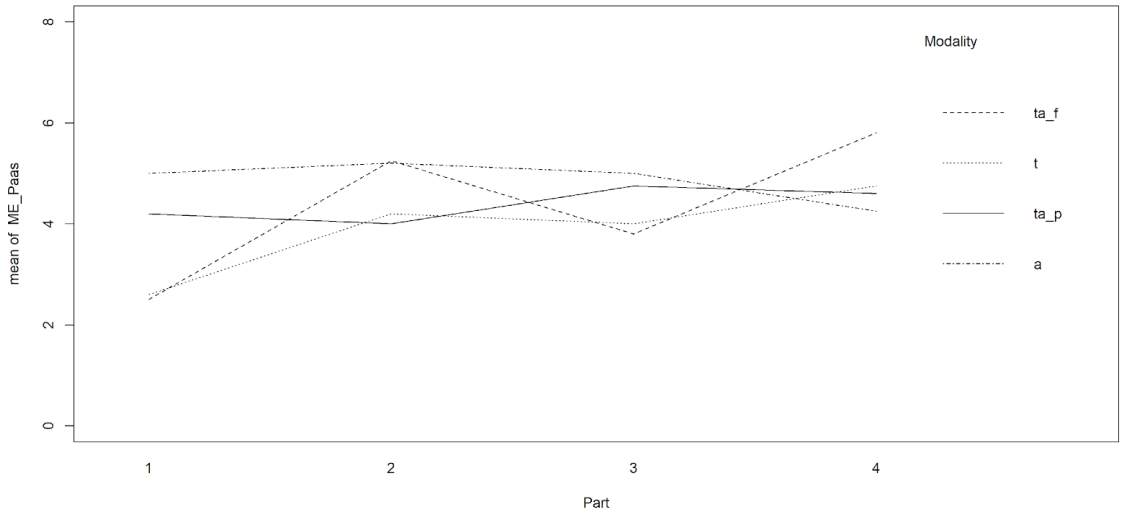


(e) Germane Load Mean (GLM-Leppink)

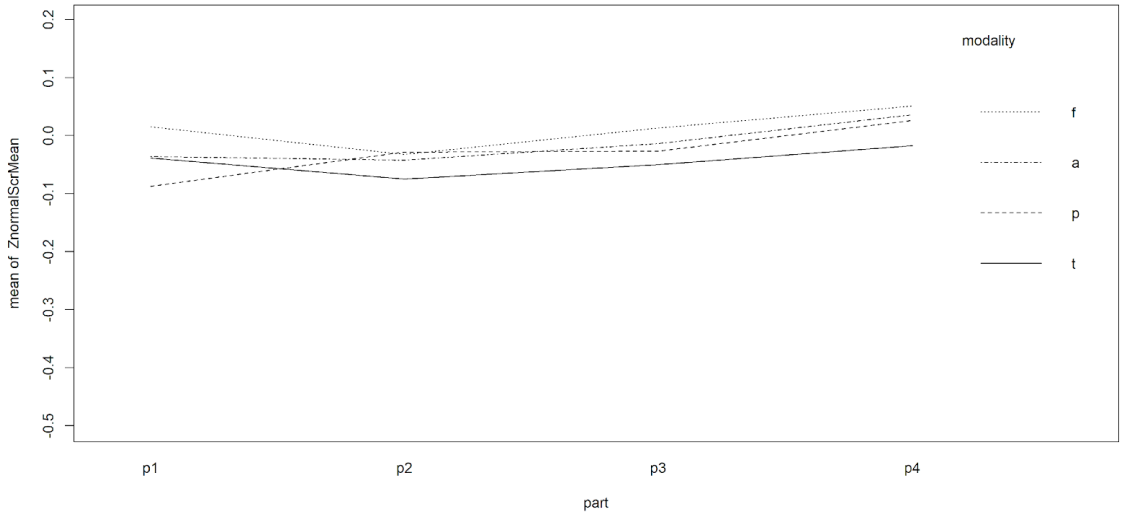


(f) Germane Load (GL-Saloman)

Figure 4.11: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 2.

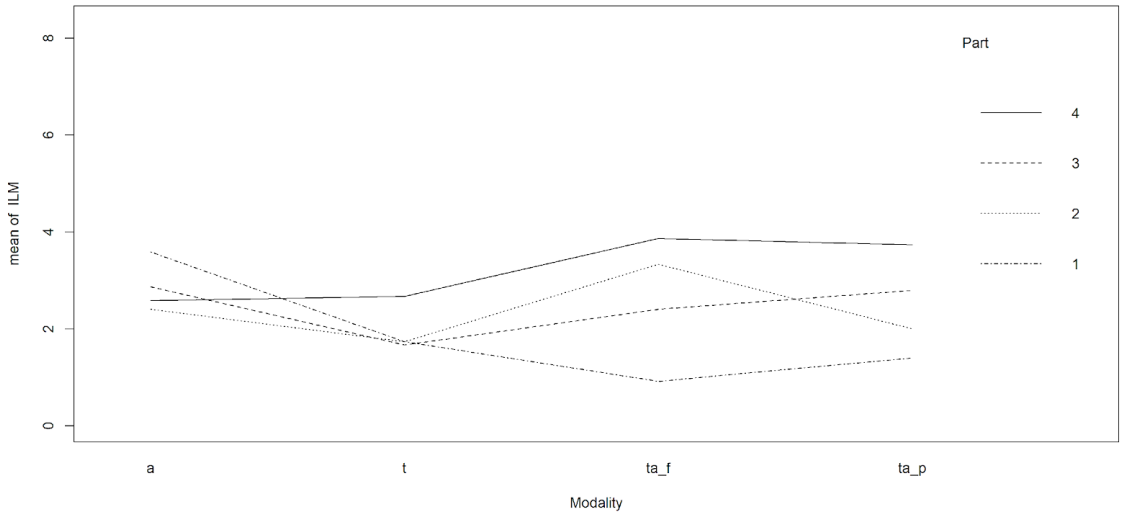


(g) Mental Effort (ME-Paas)

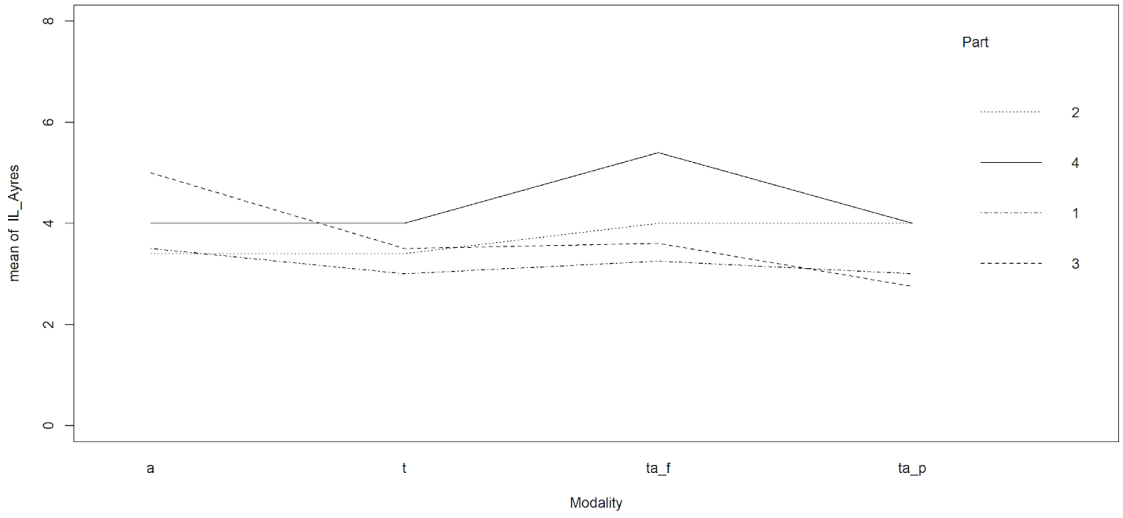


(h) EDA (Znormal SCR Mean)

Figure 4.11: The figures (a) to (h) illustrate the interaction plots (modality-redundancy wise) for the subjective scales and EDA values of Group 2.

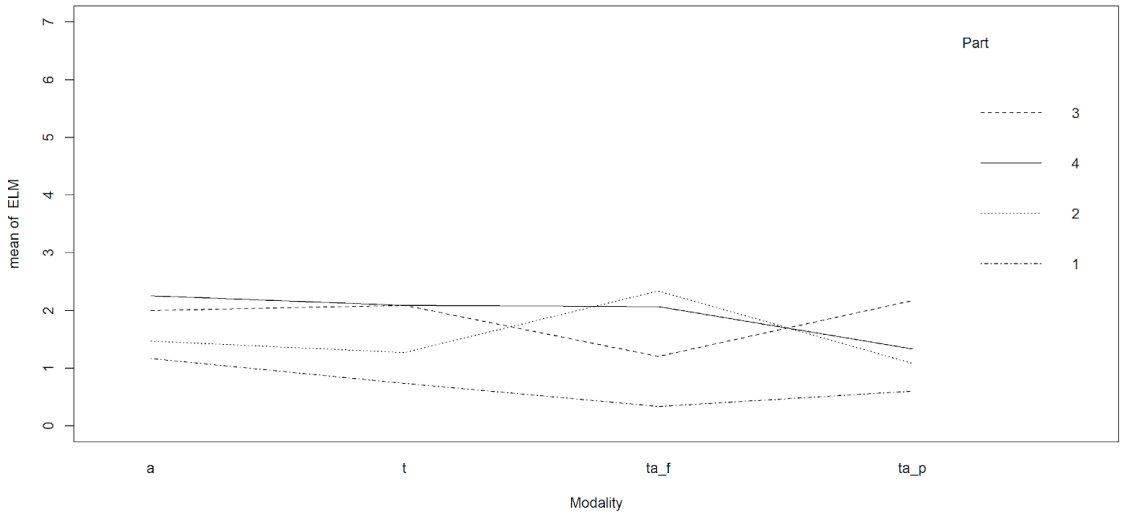


(a) Intrinsic Load Mean (ILM-Leppink)

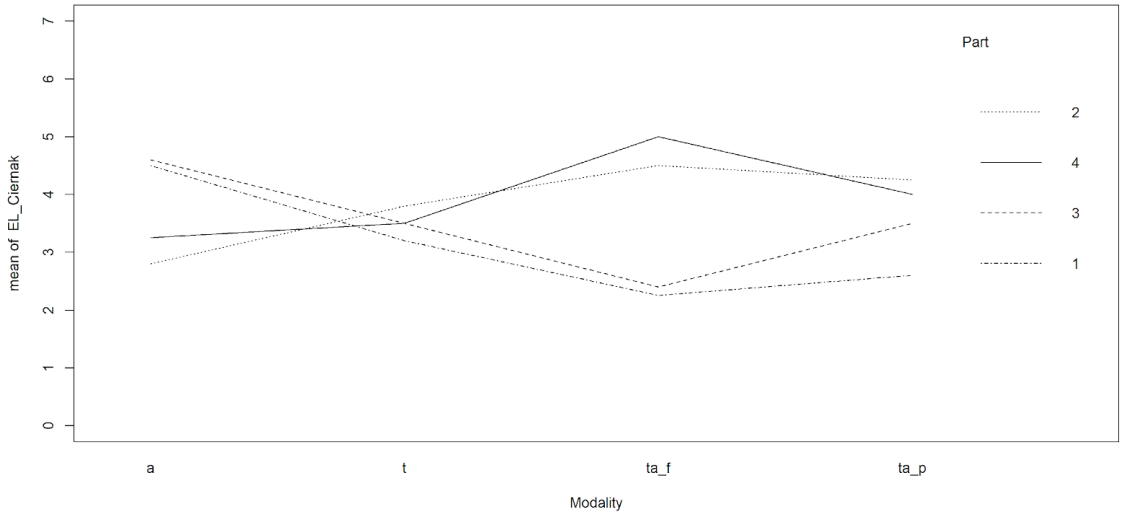


(b) Intrinsic Load (IL-Ayres)

Figure 4.12: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values of Group 2.

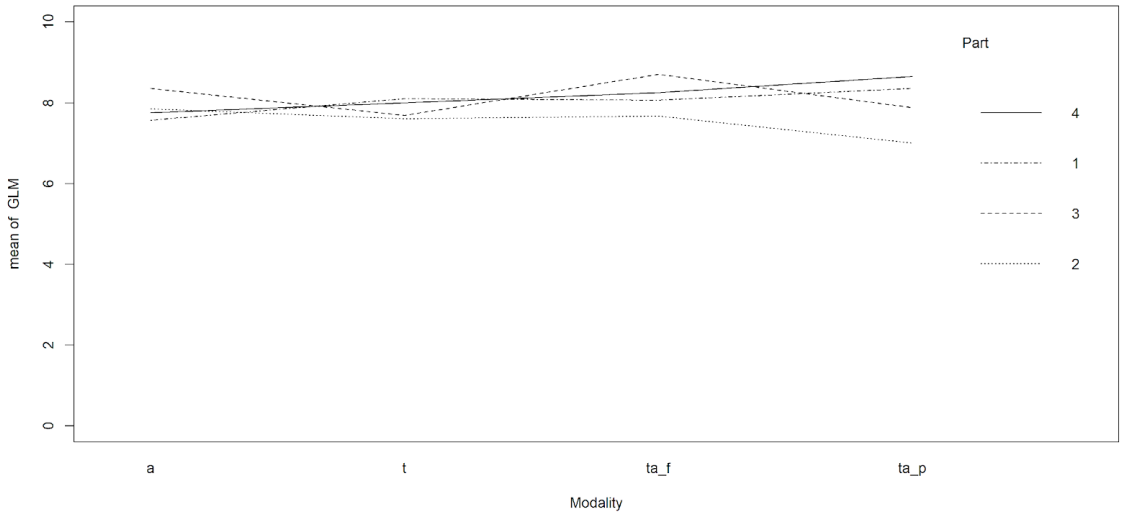


(c) Extrinsic Load Mean (ELM-Leppink)

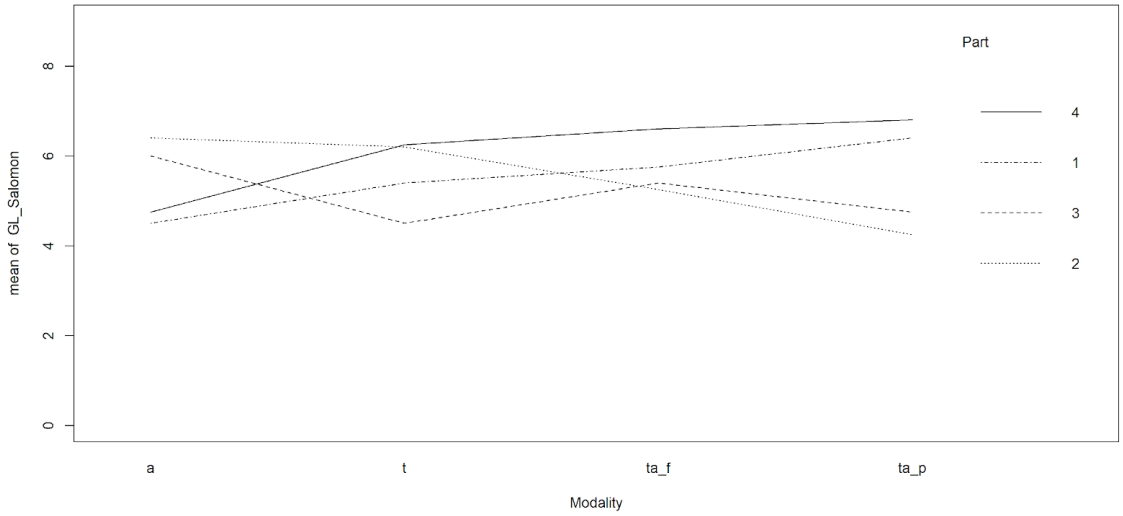


(d) Extrinsic Load (EL-Ciernak)

Figure 4.12: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values of Group 2.

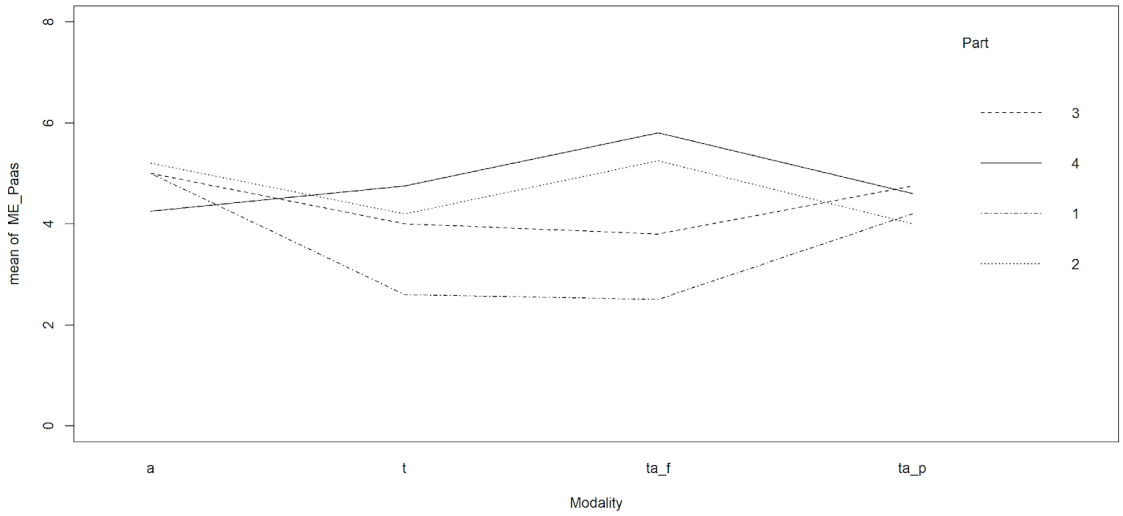


(e) Germane Load Mean (GLM-Leppink)

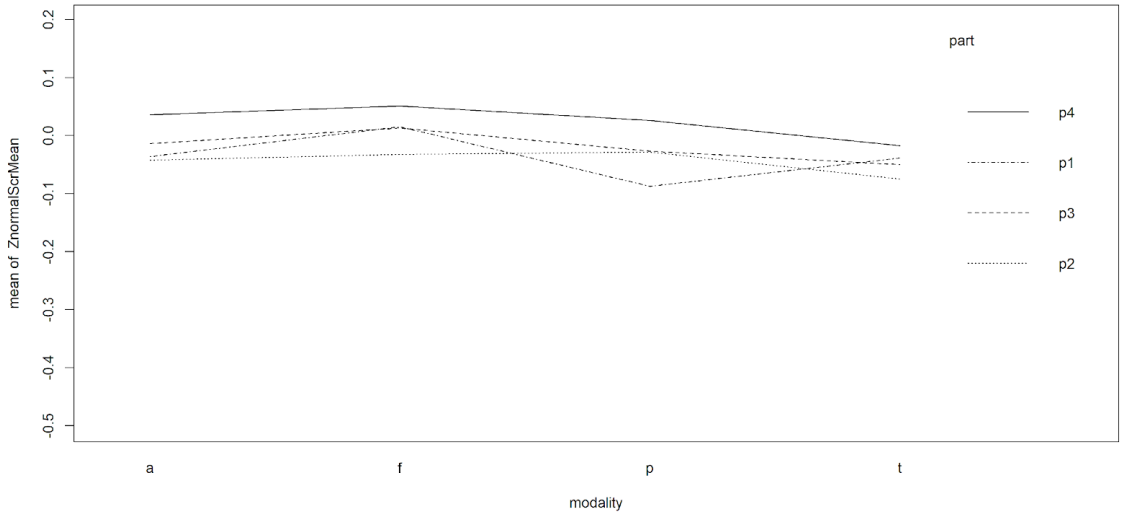


(f) Germane Load (GL-Saloman)

Figure 4.12: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values of Group 2.



(g) Mental Effort (ME-Paas)



(h) EDA (Znormal SCR Mean)

Figure 4.12: The figures (a) to (h) illustrate the interaction plots (type of content wise) for the subjective scales and EDA values of Group 2.

CHAPTER 5

"I HAVE LEARNED MORE IN VR": RETHINKING LONG-TERM EDUCATIONAL ENGAGEMENT WITH VIRTUAL REALITY

While thoughtful design is one of the subsequent factors for adoption of VRLEs, we also sought to explore the additional factors that influence their sustained adoption and integration into educational practice. Without sustained adoption, VRLEs risk falling short of their potential to contribute substantially to contemporary teaching and learning practices. Therefore, this chapter focuses on a comprehensive understanding of these factors, which is critical to bridge the gap between innovation and implementation and ensure that VRLEs deliver sustained educational value beyond isolated use cases.

5.1 Motivation

While prior research has extensively explored the applications of VR in education, most studies have focused on short-term implementations. These are often limited to isolated deployments that are not aligned within the broader curriculum [138, 139]. As a result, these VR implementations are often treated as a one-off intervention rather than a sustained pedagogical tools [140, 139]. This has led to a limited understanding of how VR might function if made available for an extended period within learning environments. To address this gap, we deployed a semester-long VR experience alongside an undergraduate course on prototyping interactive systems. The experience was aligned with the course content but offered as an optional, out-of-class activity and made accessible to enrolled students. The deployment was actively promoted within the classroom to encourage participation. Our goal was to understand how students engaged with VR when it was available as an optional learning opportunity, and what perspectives emerged from this more flexible, long-term available exposure.

For the course, we designed and developed two VR-based tutorials that simulated the operating procedures of two prototyping tools—3D printing and laser cutting—topics taught in the curriculum. The participation and interaction with the VR modules was voluntary and did not carry any academic incentives or penalties. This intentional design allowed us to observe students' engagement patterns with VR when offered as an extended, course-aligned learning opportunity. It also helped us understand their motivations, perceptions, and potential inhibitions. At the end of the semester, we conducted semi-structured interviews with 25 students who had varying degrees of exposure to the VR modules. The goal was to explore their attitudes toward VR, perceived benefits and limitations, and the challenges associated with its sustained integration in classroom learning. This study was guided by the following research questions:

- ***RQ1:*** What factors shape the students' sustained use or non-use of VR in learning environments?
- ***RQ2:*** How do students perceive and engage with VR when offered as an extended course-aligned learning opportunity, and what benefits, challenges, or barriers do they identify?
- ***RQ3:*** What practices and conditions can support the design and deployment of VR for prolonged engagement in learning environments?

Through our analysis, we identified three key findings: i) participants' varied prior exposure to VR and the diverse motivations that shaped their engagement with the modules, ii) the affordances and challenges encountered during interactions with the VR tools, including issues of usability and access, and iii) students' desires and recommendations for deeper curricular integration to support the long-term adoption of VR in classroom settings.

Our work makes the following contributions. First, we contribute to the growing body of research in HCI and educational technology by offering empirical insights that move beyond standalone deployments of VR that dominate existing literature. Second, we provide

a nuanced understanding of the factors that shape the sustained use of VR in classroom settings, highlighting students' motivations, perceptions, and the barriers they encounter in everyday educational contexts. Finally, drawing from our findings, we distill key learnings into design pathways and offer best practices and key considerations for integrating VR meaningfully and sustainably into educational environments.

5.2 Methods

We conducted the study at an engineering University in urban India from January to May 2024. The study was approved by our Institutional Review Board (IRB). Our study aimed to understand what it would mean to deploy VR in educational settings. Following this, we examined students' perceptions, attitudes, and experiences to understand their engagement and interaction with the VR. Below, we provide a detailed overview of the course structure, the VR modules introduced, participant's recruitment criteria, study methods, and data analysis approach.

5.2.1 Course Background and VR Integration

The study was situated alongside a second-year undergraduate course focused on teaching students prototyping techniques for designing interactive systems. This hands-on course introduces students to interactive product design, prototyping techniques, and fabrication tools. It runs for a duration of 16 weeks, with 39 hours of teaching consisting of lectures, lab demos and assignments. The course structure covers prototyping aspects from low-fidelity to high-fidelity covering the following five areas- prototyping using cardboard, clay, 3D printing, laser cutting and electronic components.

The introduction of VR into the course was informed by the research team's initial formal and informal discussions followed by the instructor's recommendations. Based on these insights, we introduced our modules complementing two prototyping segments of the course—3D printing and laser cutting—which focused on training students to operate these

machines. These topics were selected due to their strong procedural learning components.

Students had the opportunity to access VR modules throughout the semester, with slots scheduled at various times during the day to provide students with flexible opportunities to engage with them. To ensure VR engagement was driven by genuine interest rather than any external influence, we did not attach any incentive or penalties with using or not using the VR module. Additionally, there were no restrictions on the number of sessions students could attend. For this study, we intentionally situated the VR experience outside the formal classroom setting to observe how students engaged when participation was self-directed and not tied to academic credit. While this design allowed us to examine more flexible, interest-driven engagement, we acknowledge that embedding such experiences directly into the curriculum, with associated credit, might yield different forms of participation and learning outcomes.

This choice aimed at capturing participants' genuine perceptions and experiences with VR, particularly in relation to motivation-driven integration. Attaching incentives could have shifted participants' primary motivation toward the reward itself, thereby overshadowing or confounding the aspects of engagement, curiosity, and learning outcomes that were specifically attributable to the VR experience. For this, we intentionally situated the VR experience outside the formal classroom setting to observe how students engaged when participation was self-directed and not tied to academic credit.

5.2.2 VR Module Design

The VR tutorials for the 3D printer and laser cutting machines were developed using Unity (v2020.3.26f1). These tutorials comprised the step-by-step procedure to operate the machines with English being their medium of instruction. Both tutorials included a short pre-tutorial at the beginning, designed as an introduction and training module to familiarize participants with the VR environment. This pre-tutorial guided users on movement using the joystick, teleportation, and interacting with objects in VR. We included this to

accommodate participants who might be experiencing VR for the first time.

After the pre-tutorial, both tutorials provided a step-by-step guide on operating the respective machines. For instance, the 3D printer tutorial covered the entire process, from uploading a file from 3D printing software to external storage to adjusting basic file settings and printing the model. This included selecting the print material, installing it into the printer, preparing the machine, and initiating the printing process. Similarly, the laser cutting tutorial guided participants through selecting a file from a set of available options, choosing the appropriate material, and adjusting key laser cutting settings such as power and speed. Each step emphasized the importance of these settings and their impact on the final output.

The tutorials were self-paced, enabling participants to navigate freely, moving forward or backward through the content as needed. The laser cutter module was on an average 15 minutes of length and the 3D printer was on an average 20 minutes but the participants could explore them as long as they wanted to. The content for both the tutorials was co-compiled with the institute's Design and Innovation Lab engineer, who conducts the lab demonstrations of the machines for this course.

5.2.3 Participant Recruitment and Data Collection

The recruitment of participants for this study was facilitated by the course instructor at our university, with 88 students enrolled in the course. Course materials, assignments, and announcements were managed through Google Classroom and the course's student mailing list. The instructor provided us with access to both platforms, allowing us to share study details and updates at pre-approved times. We began by posting an introduction to the study along with an invitation for students to participate. Throughout the semester, we periodically released schedules for available time slots, allowing students to sign up for VR tutorial sessions at their convenience. Regular announcements and reminders were sent via Google Classroom and the mailing list to keep students informed about new slot

(a) (b) (c)

Figure 5.1: These figures illustrate the VR tutorials used in our study. (a) represents the pre-tutorial that preceded both our modules to train students with basic VR navigation and interactions. (b) represents the 3D printer VR module. (c) represents the laser cutting machine VR module.

openings and encourage participation. To take part in the study, students were first required to provide informed consent and complete a demographic questionnaire assessing their prior exposure to VR and their perceptions of learning in a VR environment. At the time of their scheduled session, students were briefed on the study's objectives and reminded that they could pause or withdraw at any time. Following the briefing, participants engaged with the VR tutorial for either the 3D printer or the laser cutter, depending on their selection. The tutorials were delivered using Meta Quest Pro headsets, providing an immersive learning experience. The tutorials took place in a dedicated room in the same building where the lectures for the course were conducted. The tutorial setup is illustrated in Figure 5.1

Out of these 88 students enrolled in the course, 22 students attended our tutorials. Among these 22 students, 17 participated solely in the 3D printer tutorial, while 5 engaged in tutorials for both the 3D printer and the laser cutting machine. No student attended the tutorial for only the laser cutting machine, and none of the students came for repeated exposure to a tutorial attended before. Table 5.1 illustrates the participant demographics. The participants had a mean self-reported experience with VR of 2.2 (from 1= Not at all experienced to 5 = Extremely experienced and use VR on a regular basis). 66 students did not attend either of our tutorials. Among them, 20 had reserved slots but failed to attend despite receiving multiple follow-up reminders.

Finally, at the end of the semester, we invited all enrolled students—regardless of their level of exposure to the VR tutorials e.g., single session, multiple sessions, or none to partic-

Table 5.1: Participants' Demographic Table where M represents Male and F represents Female

Session Details	Attended VR module	Attended Interview
3D Printer only	17 15 M, 2 F	9 7 M, 2 F
Laser Cutting machine only	0	0
Both	5 4 M, 1 F	4 3 M, 1 F
None	66 54 M, 12 F	12 7 M, 5 F

ipate in a brief interview. We conducted 25 semi-structured interviews with the prospective participants who responded to this follow-up communication. Four participants out of these had attended both the tutorials, nine had attended only one tutorial and twelve participants had not attended any VR tutorial. The interviews typically lasted for about 20-30 minutes. Participants were compensated for their time (only for the interviews) with Amazon gift vouchers.

5.2.4 Data Analysis

For this study, we first began by transcribing and translating the recorded data. The interview data were divided between the thesis author and one of the co-authors associated with the study for the purpose of parallel coding and verification. We then subjected the data through an iterative thematic analysis [141]. In the initial phase of coding, the thesis author and a co-author independently performed line-by-line coding of all transcripts. To ensure consistency, the codes were then reviewed and aligned as a group. The entire research team actively participated in this process through regular discussions. For instance the initial example codes included *"peer influence," "VR learning curve,"* and *"attrition factors."* Finally, we synthesized these into high-level broader themes, such as *"Motivation Spectrum," "Participant Reflections,"* and *"Opportunities and Reflections."*

5.3 Findings

We now present our findings, organized into three major themes. We begin by offering an overview of the participants' prior exposure to and experiences with VR. Next, we highlight the wide spectrum of motivations for attending or not attending. We then offer a nuanced understanding of their interactions with the VR technology, highlighting both the challenges and opportunities it presents. Finally, we present the participants' desires and recommendations for using VR in classrooms to foster long-term adoption. In the quotes that follow in the sections below, PW# refers to participants who attended the VR tutorial, while PN# denotes those who did not.

5.3.1 From Exposure to Engagement

Participants' Prior Exposure to VR

We noted that the majority of our participants already had some preliminary-level exposure to VR. This exposure primarily came from public settings such as gaming arcades or installations in shopping malls, where they engaged in recreational activities like watching immersive VR videos or playing basic VR games. A few participants also reported having personal access to VR headsets, either through owning one themselves or via a close acquaintance. At the same time, there were a few other students who had never interacted with VR before, making their experience with our module their first direct encounter with the technology.

However, we found that even among participants who had prior access to VR, their exposure levels were infrequent and limited in depth. We saw that these experiences were typically basic, focusing mostly on the immersive aspects of VR but offering minimal opportunities for interaction. For instance, (PW10, M) shared, *"I have only experienced one instance and that was purely just experimental and on-the-go. 15 minutes of just looking around in a virtual environment. Nothing major, nothing you know interactive. It was more*

visual."

Spectrum of Motivational Drivers

Beyond the varying levels of prior exposure, our data also revealed a broad spectrum of motivational factors influencing participants' engagement with the VR learning tutorials—ranging from intrinsic motivation to a complete lack of motivation.

Curiosity driven motivation: We found that intrinsic curiosity coupled with a desire to explore new technologies were the primary motivators for participants engaging in our VR learning tutorials. Our analysis highlights that curiosity-driven motivation played a crucial role in engagement, with participants eager to explore, understand, and interact with VR beyond mere participation. We saw that participants with limited prior exposure to VR exhibited heightened inquisitiveness where their motivation stemmed from a deep-seated curiosity about how VR works and its potential applications. We noted that participants' motivation was reinforced by the excitement of engaging with novel technology, with many perceiving VR as *"techie," "cool,"* and *"advanced"*. This perception not only enhanced their interest but also drove their engagement and attendance, as the appeal of both the medium (VR) and the subject matter (3D printing) played a crucial role in their participation. For example (PW3, F) said, *"it fascinates me using VR headsets, and it's cool to use. I was excited to try it out."*

Peer driven motivation: We also observed that participation was not solely driven by personal interest but was strongly influenced by peer dynamics, social connections, and the desire to be part of shared experiences. They expressed that for them the fear of missing out (FOMO) was a motivational driver in order to avoid being left out of group activities. This sense of collective participation enhanced the experience, making it more compelling to participate. Additionally, we also found that many participants attended the VR tuto-

rial primarily due to instructors' recommendations and the tutorial's perceived relevance to their coursework. For example (PW10, M) shared, *"many of my colleagues and friends were going. So why would I not just join in on the fun."*

Autonomy driven motivation: The other main reasons of participants attending the tutorial was their perception that physical lab demonstrations lacked value due to institutional level limitations. For example, they expressed their experience with the limited hands-on exposure and absence of autonomy in operating equipment such as 3D printer and laser cutting machine in real-world settings. We found that almost all the participants were already aware that, at the institute level, direct operation of these machines was not feasible and that learning was primarily instructor-driven. In traditional lab settings, the instructor would demonstrate while students gathered in groups around the machines, restricting individual engagement. Given that these machines are expensive and must serve an entire institute, opportunities for independent operation were limited. As a result, many participants were drawn to the tutorial because it offered them a sense of autonomy and ownership in their learning, the elements they felt were missing in the physical lab environment. For instance a student explained,

> *. . . in our courses, the laser cutting and the 3D printing part is mostly done by an assistant or the instructor, and there's no hands-on experience. I was like, I want to know what is really the process of getting stuff printed, which I think was pretty well explained by the study.* —(PW5, M)

Competence enhancing motivators: Moreover, they saw these sessions as an opportunity to deepen their understanding of 3D printing and its applications, particularly in relation to their PIS course assignments. Furthermore, many of them also believed that engaging in supplementary tutorials on class-related topics would enhance their preparedness and comprehension, making complex concepts more accessible and applicable to future coursework. As explained by a participant,

"..side by side for the 3D printer it was that it is a part of the course and it would be required later, so that was also a good point for me to register for the study." —(PW11, M)

Another reason cited by the students for signing up for the study was to compensate for a missed topic in class. They believed attending the VR tutorials could help make up for the missed content, especially if that information would be helpful later in the course. They viewed VR as the next best alternative to experiencing the topic in a real-world setting.

Actually the 3D printer session that Ma'am took in class, that I had missed. But I wanted to understand it, it will be used at many places so then I thought lets look at it in VR once, it will look a little realistic also. —(PW10, M)

Drivers for non-attendance: Beyond the diverse motivations that led students to attend our tutorial, we also observed a range of reasons among those who chose not to participate. These reasons primarily revolved around academic workload, perceived relevance, incentives, and peer influence. Many students cited excessive coursework, assignments, and academic commitments as a barrier to attending the tutorials. Since the tutorials were not mandatory and had no bearing on course grades, participants did not perceive them as essential and often prioritized their graded coursework over these supplementary sessions. As the tutorials were held outside of regular class hours, many students perceived them as an added burden rather than a beneficial learning opportunity. Some students explicitly mentioned that the absence of penalties for non-attendance further diminished their motivation to join. They also pointed out that as they did not see their friends or peers attending these sessions followed by the lack of discussion within their social circles further discouraged their participation. As explained by a participant who did not attend the tutorial,

"... the reason was that none of my friends were doing it. So I mean, I did not want to go alone and try it, so. Had I gone with my... if I had any friends who were also going, maybe I would have gone." —(PN11, M)

5.3.2 From Engagement to Attrition: Understanding VR Experiences

What stood out

All our participants, regardless of whether they attended the VR tutorials, acknowledged its unique potential to enhance both learning outcomes and experiences. They talked about the positive aspects of VR as a learning medium, specifically in the context of our modules, emphasizing the hands-on experience as the most prominent benefit. We saw that initially the participants' expectations were shaped primarily by their limited understanding of VR as an immersive medium. However, upon engaging with our tutorial, participants found that the experience not only exceeded their expectations but also shifted their perception of VR. It was because our tutorial was not only immersive but also interactive in its nature. We saw that the interactive nature of the tutorial, in particular, mostly stood out for them, broadening their understanding of VR's potential beyond immersion to include meaningful interactivity. They also mentioned that this interactive engagement enhanced their understanding beyond theoretical instruction. As explained by a participant,

> *"Like in other places that I have explored VR before, it was not as immersive. But here I was able to move, I was able to switch on the buttons, and I was able to do everything like I would have in the real-time scenario as well"* —(PW7, F)

We saw that participants highly valued VR's ability to closely simulate real-world experiences. They appreciated the opportunity to engage with virtual replicas of equipment prior to operating them in the real world, which they found both valuable and reassuring. This appreciation stemmed largely from VR's affordance to address the limitations of traditional training methods. Importantly, they emphasized the autonomy offered by the VR environment throughout the tutorial which they felt was missing in their physical lab demo. For instance, (PW4, M) stated *" I'll say picking up the objects from the rack, and like filling the filament, and the 3D printer, etc. were good, so like it made it more closer to the*

real things." Furthermore, they highlighted another key advantage, which was the freedom to make mistakes without real-world consequences. In addition, they also mentioned that VR reduced the potential risks associated with using real machines in physical settings. This perceived safety encouraged exploration and experimentation, enabling them to imagine and rehearse diverse scenarios without the fear of damaging resources or committing critical errors. As one of the participant shared,

> *"Human errors can lead to collateral damage, and anything worse can happen, but in VR you can make infinite mistakes and perfect yourself. I think is the biggest capability of VR"* —(PW2, M)

In addition to the above, we also found them to emphasize the role of VR's visualization capabilities in enhancing their understanding and comprehension of the learning material. They appreciated how VR allowed them to see what the final prototype might look like, examine objects from multiple angles, and view machines from different perspectives. We further noted that going through the 3D printing and laser cutting process in VR improved their ability to visualize and plan their own designs. Participants reported better conceptualization of their assignments related to the course topics resulting in better outcomes. As one of the students explained,

> *"VR can have the full expanded view, the bird's eye view. And seriously, I have learned more in VR than I can say about the demonstrations or my teachers or instruments or online tutorials"* —(PW2, M)

Apart from the above, we noted a wide range of other factors that participants believed to have a positive impact on their overall learning experience. We saw that they found VR to promote higher focus and attention, minimizing the distractions typically present in classroom environments. Moreover, the fun and game-like enjoyment offered by VR made the learning process more engaging and enjoyable, contributing to an overall positive and

stimulating learning experience. Participants also favored the option provided by VR to learn at any location and time, unrestricted by class schedules, and to tailor the learning pace to their individual preferences. They stated that it was convenient, alleviated the burden of coordination, and granted students the autonomy to decide when, where, and how often they wish to study a subject. Participants also perceived that the VR environment supported better retention of the learning content compared to traditional materials, a view that is in accordance with prior research indicating the positive influence of VR on retention [7]. They found that actively engaging with procedural tasks in the virtual environment boosted their confidence in applying these skills in real-world contexts, thereby supporting knowledge transfer which is mostly the primary objective in procedural learning. For example, a participant shared,

> *"This I really like about VR that this [attended the tutorial] I had done quite sometime before, I think months ago, but then I know, remember laser cutting also and 3D printing also. So that I really liked. It [retention] was very high in VR, it was very less in class. Like even if I make and keep notes in class, that much of learning does not happen. I remember making PIS notes, but for VR I did not make any notes as such but I remember every step from VR. In short, retention wise it is the highest. If someone suddenly gives me the machine, then I can even demonstrate all the work."* — (PW2, M)

Opportunities Identified

Throughout our data, we noted that participants consistently recognized the potential of VR learning environments and identified various opportunities where these could be leveraged to enhance learning experiences. We observed that after experiencing VR's capabilities, participants were able to easily relate it to both past and current learning situations, clearly envisioning how and where VR could contribute to enhancing their overall learning experience. They highlighted the high retention affordances of VR, emphasizing its usefulness

in subjects that benefit from visualization and hands-on learning, such as physics, chemistry, biology, mathematics, and digital circuits. Additionally, they acknowledged its role in storytelling-based subjects like history and geography, where immersive experiences can enhance engagement and understanding. Beyond traditional academic subjects, participants also spoke about the potential of VR in skill development and capacity-building courses, particularly in vocational training, where interactive and experiential learning can significantly improve retention and practical application. For instance, a participant explains,

> *I think it was benzene or other things, and they had like different kind of shapes for every molecule, and to imagine what that looks like. And you know there were, I think there was some part of it that had something to do with the orientation of molecules in space, and how the molecule was not stable. And so you had to imagine why... I think studying that kind of stuff would definitely, you know, help would have helped had I done it using something like a VR headset.*
> - (PN11, M)

Beyond its applications in traditional education and skill development, many participants also highlighted the potential of VR in remote learning, particularly in homeschooling and cases requiring procedural learning. They spoke about VR holding the potential to bridge the gap between physical classrooms and home-based education by providing immersive, interactive, and engaging learning experiences. For example, students can participate in virtual laboratories, explore historical sites, or engage in real-world simulations, making subjects more tangible and easier to grasp. They also mentioned that VR can make learning more engaging and appealing, offering an opportunity to enhance focus and improve attention spans, which could lead to better learning outcomes.

Challenges Encountered and Attrition Factors

Although participants enjoyed interacting with the VR experience, they also faced several challenges while using it. Specifically, we identified two main challenges that consistently emerged across participants' experiences, both of which have been widely discussed in prior literature. The first was simulator sickness, and the second was the steep learning curve involved in interacting with the VR environment. During the interactions, a few of our participants experienced mild symptoms such as headache, dizziness, and eye strain. We did not observe any cases where participants experienced symptoms severe enough to require discontinuation of the VR session. Further, we observed that some participants faced difficulties in navigating the virtual 3D space, using VR controllers to interact with the virtual objects, and aligning their physical movements with the virtual response they got. However, gradually after some time, these issues diminished with repeated use, suggesting that the challenges were manageable as they became more familiar with the interface. As (PW11, M) mentioned, *"It took some time in the starting to understand it, but then after sometime I got comfortable."*

We observed that among both the participants who attended the tutorial and those who did not, generally had a positive attitude toward VR. However, we still noticed a high attrition rate regarding attending follow-up tutorials or continuing engagement after a single exposure. This seemed to be largely because participants were primarily interested in experiencing the novelty of the technology, rather than sustained use or learning. Further, they highlighted that modules with only minor contextual differences were not sufficient to sustain their motivation for continued engagement with the VR tutorials. Participants also cited the lack of immediate incentives or direct added value to course outcomes as another major reason for missing follow-up sessions. We saw that while alignment with the course structure initially motivated participants to gain exposure but the absence of a direct impact on graded activities and the lack of any direct incentives to participate discouraged many from signing up for or returning for additional tutorials. As shared by one of our

participants,

> *"I think it was dependent on the fact that I already explored a similar experience. So I kind of knew what the laser cutting experience might have been. So I was really interested the first time."* —(PW1, F)

Another commonly cited reason for missing the follow-up sessions was scheduling conflicts with other high-priority academic commitments during the semester. Since the VR tutorials were optional and not linked to graded coursework, students reported difficulty in allocating time for them, often prioritizing activities that directly impacted their academic performance. We noted a significant drop in the participation during the latter half of the semester. This period was typically associated with a higher academic workload, where we observed students were grappling with multiple final project deadlines, assignments, and examinations. As a result, we found that even those who were genuinely interested in the sessions found it difficult to prioritize them in the absence of direct, graded benefits. As one of the participant recalled,

> *"Being very frank, I did think of attending one, but because of the workload of other subjects and everything... the next day we had a quiz or something, so that's why missed it."* —(PW6, M)

5.3.3 Participants' Desires and Recommendations

Although our participants recognized the potential of VR for enhancing learning, they also expressed specific desires and offered recommendations for improving the overall VR learning experience. In particular, they suggested ways to integrate and design future VR modules more effectively. They also highlighted considerations for making them more user-friendly and engaging. Participants recommended that the VR tutorials offered outside of regular class hours should instead be integrated into scheduled classroom time.

They mentioned that when such sessions are held separately from the main course structure, students are less likely to attend and may not fully understand or appreciate their value. Embedding the tutorials within the formal course schedule, they suggested, would increase participation and ensure that students perceive them as a meaningful part of their academic learning. Additionally, participants emphasized the role of VR tutorials in complementing classroom learning either as a preparatory tool to build foundational understanding before engaging with course material or as a supplementary aid to revisit and clarify concepts that remained unclear after class. Some also expressed a desire for on-demand access to supplementary VR modules, enabling them to revisit specific topics when classroom instruction alone did not fully clarify the concepts. As one participant explained,

> *"...If maybe imagine there's a QR code in your booklet, and when you scan it..you go to some interface where you can have a better experience of what they were trying to say in words... So imagine a similar kind of thing for students in the future, where maybe scanning or tapping on a link can open something in your VR for visualizing, which was not explained in a good manner in the text."* —(PW6, M)

Others saw value in integrating it as an early exposure tool, specifically for subjects that may require strong spatial and visual comprehension, believing it could enhance familiarity with complex topics and improve overall learning outcomes. For instance, (PW8, M) mentioned, *"If we had online VR Labs to help us practice before the real lab, it would have gone a lot better I feel."* Students highly stressed having a blended learning model where VR serves as a complementary learning tool rather than a replacement for traditional methods. They further recommended providing alternative, easily accessible instructional mediums for students who may not be comfortable with VR or need time to adapt. While highlighting various ways to integrate VR into their mainstream learning, participants also stressed the need for its thoughtful integration all along. All participants emphasized the importance of thoughtful integration of such technologies. They recommended that VR

should be selectively incorporated only into courses or specific components where its affordances clearly enhance learning outcomes or support targeted educational objectives. As PW2 explains,

> *"There should be a balance, I never said in coding that VR should be there. Because in coding, visualization can happen without VR as VR does not have much role to play, it is like calculations."* —(PW2, M)

Participants expressed an expectation that the VR learning environment should closely emulate real-world procedural conditions, capturing even subtle operational details to ensure authenticity and instructional relevance. Additionally, they emphasized the importance of optimizing VR environment design to reduce cognitive load. They recommended minimizing unnecessary movement, avoiding excessive verbal content, incorporating navigational support such as cues, supporting modular content delivery and ensuring visual and experiential appeal. Participants believed that such measures could be helpful in enhancing usability and the overall experience.

Finally, students shared their expectations around the need for dedicated training modules to help them get comfortable with using VR to address the associated learning curve. The pre-training section offered by our modules served as an introduction to essential interactions. However, the participants expressed a need for more extensive and focused preparation to feel fully comfortable navigating and operating within the VR environment. They emphasized the need for separate, focused training sessions to build familiarity and ease of use, viewing this as a critical factor for encouraging wider adoption of VR in learning environments.

> *"I think just before the class [semester] starts... there's a 3-day [refresher] module. So if it's possible to do it during that, because before every semester there is always a module which goes on....I think during that time most of the students are normally free."* (PN4, M)

5.4 Discussion: Best Practices and Considerations

This study examined the deployment of VR as a complementary learning tool introduced outside the formal classroom setting. Our findings revealed an overall positive response to the VR experience among students who participated in the tutorials, particularly regarding its immersive and engaging qualities. Interestingly, even students who did not attend the sessions expressed curiosity and a generally favorable attitude toward the technology. However, we also identified several limiting factors such as logistical barriers and a lack of awareness about VR's pedagogical capabilities that currently hinder its sustained integration into educational environments. These insights suggest that for VR to move beyond novelty and become a meaningful part of long-term learning, it must be thoughtfully introduced, supported, and contextualized.

To draw from our findings more deeply, we build on learning theories to understand how and why certain aspects of VR learning environments were more or less effective. Our data revealed recurring patterns that closely aligned with core constructs from learning theories. Elements such as autonomy, competence, relatedness, and novelty central to frameworks like Self-Determination Theory (SDT) consistently surfaced in participants' experiences. These elements functioned both as facilitators and inhibitors of engagement. Importantly, we note that they are not isolated; rather, they are deeply interconnected, with each shaping and being shaped by the others in practice. This interplay highlights the need for careful, holistic design approaches. Based on this synthesis, we outline a set of best practices and design considerations to guide the sustained use of VR in classroom learning.

Fostering Autonomy: Across our data, *autonomy* emerged as an important factor shaping students' engagement with the VR learning environment. In conventional classroom or lab-based settings, students often experienced limited autonomy. This was largely due to institutional constraints such as high equipment costs, operational complexity, and safety

concerns. As a result, learning was typically delivered through instructor-led demonstrations, leaving little room for independent exploration. We saw that VR helped bridge this gap by providing a simulated environment that allowed students to engage directly with the learning content. It offered them the freedom to explore at their own pace, without the risk of damaging equipment or making irreversible mistakes. This shift not only increased students' sense of control over their learning process, it also reflected the SDT's concept of autonomy, which emphasizes the importance of choice and personal agency in motivating learning [142]. For example, as seen in Section 4.2, VR enabled safe experimentation, temporal flexibility, and freedom to fail, all of which contributed to a strong sense of learner autonomy. These findings suggest that designers and educators should not only acknowledge autonomy as a built-in strength of VR, but also actively seek ways to amplify it. We suggest designing VR experiences that emphasize learner autonomy can lower barriers to engagement and support deeper, self-directed learning. To fully leverage this affordance, it is important to embed design strategies that actively promote autonomy. These include offering students choices in module selection [143, 144, 145], enabling control over pacing and sequencing [146, 147, 148], supporting multiple learning pathways [143, 146], explaining the rationale behind learning activities, and using non-directive language [149, 148]. Integrating such elements can enhance student motivation and position VR as a meaningful component of sustained classroom learning.

Building Competence: Our findings reveal a *competence* paradox in students' early engagement with VR-based learning. While the technology afforded greater autonomy, many participants initially struggled to feel effective when navigating the unfamiliar environment. This challenge was tied to a steep learning curve involving movements, interactions, and system controls. As a result, learners' perceived competence, a central need within SDT [142], was temporarily undermined. Even with a pre-tutorial designed to introduce basic VR interactions, participants reported difficulties that disrupted their learning experi-

ence. This early discomfort often acted as a barrier to engagement, echoing prior research that links perceived competence with motivation and sustained use [150].

However, once learners overcame these initial hurdles, many reported a renewed sense of confidence. Practicing tasks in VR helped them feel capable of applying those skills in real-world settings. The hands-on, interactive nature of the environment supported experiential learning and reinforced mastery. Participants later reflected on how VR could support subjects they had struggled with previously, shifting their perception of its value in education. These reflections highlight VR's potential to build competence and confidence through immersive, embodied learning. Yet, to fully leverage this potential, it is critical to address the initial barriers that may hinder engagement.

We recommend building VR Literacy as a foundational step. Structured pre-exposure tutorials which are incremental, context-sensitive and scalable across applications can help navigate onboarding barriers by building users' technical competence [151]. These multi-staged tutorials can gradually increase in complexity from environmental orientation, to basic actions, to complex interface interactions and cognitively demanding tasks. We believe that in addition to building users' technical competence, these sessions can also help students unlock the potential the technology holds by giving them a taste of its affordances. Our results showed that this awareness fosters motivation and helps position a broader value of VR in diverse learning contexts. We also recommend including a clear expectation-setting disclaimer when introducing VR in educational contexts, which has seen value in setting early on expectation while engaging with content in VR [152]. Communicating upfront that VR involves a learning curve one that is both normal and temporary can help manage user frustration and reduce early dropout. When students are made aware that initial discomfort or unfamiliarity is part of the process, they are more likely to persist and engage long enough to experience the medium's pedagogical value [146]. A simple but explicit disclaimer at the outset, paired with supportive onboarding, can thus play a critical role in sustaining engagement and fostering a smoother transition into immersive learning.

Promote Relatedness: To effectively integrate VR into education, our findings underscore the need to strengthen *relatedness*, a critical yet often underemphasized component of learner engagement. In SDT, relatedness refers to the sense of social connection and belonging that supports motivation and engagement [142]. Our study revealed that students' motivation to engage with VR was closely tied to their social networks and peer dynamics. Because our VR tutorials occurred outside regular class time, students often decided whether to attend based on whether their peers were participating. Those who joined commonly cited their friends' presence as a motivating factor, while those who skipped often mentioned that no one from their social circle was attending. This indicates that relatedness was not only important for social comfort but also shaped students' willingness to engage with the technology. To support relatedness, we recommend that any integration of VR into learning environments include a mandatory introductory session. Such exposure not only increases students' understanding of the medium's potential but can also generate social momentum around its use. Collective participation can create a shared sense of novelty and belonging, encouraging broader adoption. Current VR learning applications, including ours, tend to center on individual experiences [153]. While these can be beneficial for focused learning, they may lack the social cues that sustain motivation. Designing for peer visibility and interaction, such as through collaborative tasks, shared progress boards, or badges can help bridge this gap. Prior work in gamified learning environments supports the use of such social features to enhance relatedness and motivation [154]. Moreover, advancements in collaborative VR [155] provide an opportunity to rethink how social connections are supported in immersive settings. VR environments can be designed to support trainer–trainee or peer-to-peer collaboration, offering opportunities for group assignments or co-located experiences that mirror traditional classroom dynamics.

Finally, our participants pointed to an expanded form of relatedness, one that extends beyond interpersonal connection to include connection with content. VR's ability to sim-

ulate real-world experiences created a stronger sense of alignment with course material compared to other digital tools. This content-based relatedness is not yet fully captured in existing theoretical framings but may be particularly salient in immersive learning environments. Expanding SDT's scope to include this dimension could offer a more comprehensive understanding of motivation in VR-based education.

Optimizing Novelty: While SDT traditionally emphasizes autonomy, competence, and relatedness as core psychological needs [142], recent extensions highlight *novelty* as an additional driver of motivation [156]. In our study, we found that novelty played a dual role initially sparking curiosity and attendance, but later contributing to disengagement as its appeal diminished. Participants frequently cited their initial interest in VR as driven by its novelty. The excitement of trying something new, such as operating a 3D printer or exploring a virtual workshop, motivated their first encounter. However, repeated exposures to similarly structured tutorials were perceived as redundant. Some explicitly avoided sessions they assumed would mirror previous ones (*"I saw the 3D printer tutorial, so I figured the laser cutting one would be the same"*, (PW1, F)). This phenomenon echoes prior work in gamification and educational technology, where systems often see a spike in user activity during early encounters, followed by sharp declines once the novelty wears off [157, 154]. Known as the "hedonic treadmill," [157, 154] this cycle of initial engagement followed by diminishing interest highlights the need to thoughtfully manage novelty in learning systems. While diminishing novelty can reduce engagement, at the same time too much novelty can also be counterproductive. Particularly for VR, this may lead to overwhelming stimuli impairing cognitive performance or lowering users' sense of competence. This tension calls for a balanced approach such as *designing novelty-optimizing* rather than novelty-reducing systems. Drawing from Cors et al.'s work on scaffolding in open-ended learning platforms, we argue that early exposures should intrigue rather than overwhelm, supporting a gradual, curiosity-driven acclimatization to VR [158].

Moreover, many current VR learning modules are static and repetitive, failing to offer new learning value beyond the first interaction. While they may function well as one-time practice tools, they struggle to support long-term engagement without updated content or escalating challenge levels. To address this, we advocate for dynamic VR modules that evolve with the learner. Such modules could offer multiple difficulty levels, adapt to users' progress, and present branching scenarios tied to course objectives. In our study, participants expressed a desire for environments where they could experiment with different outcomes and iterate on decisions mirroring real-world problem solving. These interactions not only reinforced content understanding but also deepened students' investment in the learning process. With recent advancements in machine learning and adaptive educational systems [159, 160], developing personalized and responsive VR content is increasingly feasible. These systems can tailor the pace, complexity, and feedback to individual learners, promoting sustained engagement while respecting diverse learning trajectories. Ultimately, to fully realize the potential of VR in education, novelty must be treated not as a fleeting hook but as a dynamic, scaffolding design element. By calibrating novelty with a balance, we can create immersive learning environments that not only attract attention but sustain over time.

Context-aware Integration: Students in our study viewed VR not as a one-size-fits-all solution but as a tool with value in specific learning contexts. They saw VR valuable in visualization-heavy and experiential courses such as organic chemistry, digital circuits, and history, but not in subjects like programming where VR added little. Students viewed VR as a *complementary medium*, most effective when part of a blended learning model [161] rather than a replacement for traditional methods. This aligns with research advocating for hybrid pedagogies that build on, rather than disrupt, existing instructional scaffolds.

However, we bring to the fore that its integration must be thoughtful. Students emphasized the need for VR to be embedded *within class hours* and accompanied by *incentives*

when introduced outside classroom hours. When offered as an optional, out-of-class activity, it often became an added burden. These concerns align with literature on *curricular overload* when new technologies are added without revisiting existing course structures [162, 163]. We also advocate for *co-creation of the curriculum*, where VR modules are aligned with course objectives, and less relevant content is adjusted or removed. They also stressed the importance of timing, assessment linkages, and decisions around mandates and access.

Accessibility remains a key challenge. Simulator sickness and discomfort with VR devices were common, reaffirming existing concerns [106]. As such, *alternatives*, such as 2D interfaces or physical models, must be provided to ensure inclusive participation. In short, VR should be *selectively and flexibly integrated*, with alignment to course goals, incentives for use, and accommodations for diverse learners. When thoughtfully embedded, VR can offer unique pedagogical value where traditional media fall short.

5.5 Limitations

We acknowledge the lower participant numbers in the subsequent stages of the study, resulting from our chosen methodological approach, as a limitation of this study. However, this was not a result of targeted recruitment but emerged organically during participation. Our study was situated outside the formal classroom setting, which influenced how students engaged with VR. We believe that integrating such experiences directly into the curriculum, with academic credit, could shape different forms of engagement and learning. We also observed a gender imbalance among our participants, which can be attributed partly to the methodological approach employed and partly to the persistently skewed gender ratios within engineering institutes in the country. With this, we acknowledge this tradeoff between capturing genuine perceptions and behaviors and maintaining participation numbers. We recognize that a more balanced and diverse participant pool could yield broader insights, and we aim to address this in future explorations. While we do not claim gen-

eralizability, our intent was to explore what meaningful, sustained VR integration might look like. This vision is shaped by our strong desire to support long-term, inclusive learning environments. Therefore, we present this work to be interpreted as a contribution that gestures toward possibilities rather than definitive conclusions.

CHAPTER 6

ADVANCING VRLES: SYNTHESIS AND ANALYSIS OF A DESIGN SPACE (ONGOING WORK)

This study was conceived as a complementary strand to the empirical investigations presented in Chapters 3 and 4. The preceding chapters of this thesis examined both the design and adoption of VRLEs, highlighting that while sustained adoption can be supported by leveraging established pedagogical theories, there is an absence of a unified framework to guide the design of VRLEs systematically. Our findings indicate that design practices are often fragmented and ad hoc, lacking a structured approach that leverages design theories from the outset. Addressing this gap, the present chapter builds upon insights from the earlier empirical studies and the broader literature to develop a foundational design framework for VRLEs. In this work, we map the design space of VRLEs through a semi-systemic review and morphological analysis. The aim is to provide a comprehensive structure that supports both researchers and practitioners in making principled, theory-informed design decisions for VRLEs in diverse educational contexts.

Currently, the study has advanced through the stages of literature corpus identification, screening, and iterative classification and organization of findings into potential dimensions. Eight preliminary core dimensions (five representational and three interactional) and two auxiliary dimensions have been identified, each with emerging value sets. These dimensions are organized into the overarching categories of representation and interaction, forming the basis of the proposed framework. Early visual mappings of these dimensions already reveal recurring patterns and underexplored areas within current VRLE implementations. These preliminary findings provide substantive insights that directly shape principled VRLE design approaches, thereby supporting the thesis's overarching goal of enabling and sustaining VR integration in educational practice.

Recognizing this need and informed by the preliminary outcomes to date, the present study is directed towards achieving the following objectives:

1. Synthesis of a design space by creating a structured framework that organizes key design dimensions and their corresponding value sets, thereby providing a foundation to inform and guide VRLE design decisions.

2. Assess the synthesized design space by systematically classifying existing VRLEs, identified through the literature review, using Zwicky Box analysis and showcase its descriptive capability.

3. Reveal design opportunities by analyzing underrepresented or unexplored regions of the Zwicky box, thereby identifying gaps, trends, and alternative configurations for innovation.

4. Enable comparative analysis by using the design space to evaluate how variations in dimension values influence the effectiveness, suitability, and optimization of VRLE designs.

6.1 Methods

For this work, we employed an iterative, semi-systematic review process, combined with a remediation approach [164], to synthesize the VR design space. The semi-systematic review process is particularly useful when investigating a broader, multidimensional topic connected with several research areas to make an overview of the topic [165, 166, 167, 85]. The remediation approach involves translating elements from one media system to another enabling them to grow and co-evolve together while borrowing elements, standards, and ways of thinking from one another. It enables us to draw from varied sources and media to construct a holistic view. There are many diverse approaches to developing, structuring, and articulating design spaces [78] within the literature, with varying complexities. Given these variations, developing a comprehensive design space faces inherent

challenges, beginning with the initial scoping and followed by defining the principal axes and dimensions. Our methodological choice was mainly informed by the dispersed nature of VR design and affordance discussions, which span multiple domains and use varied terminologies in the literature. This diversity mainly renders conventional systematic review filtering insufficient for comprehensively capturing the breadth of the design space, making a semi-systematic review coupled with a remediation approach our preferred choice. Furthermore, we apply morphological analysis [100] to structure, represent, and systematically examine this space. This analysis, specifically through the Zwicky box technique, allows us to model this space as a multi-dimensional problem, systematically exploring combinations of parameters to reveal patterns, gaps, and opportunities within the design space.

6.1.1 Synthesis of the Design Space

To synthesize the design space, we employed an iterative, semi-systematic process that builds on the prior work and the research team's experience in VR, HCI, and education. In this, we carried out the snowballing methodology described by Wohlin [168] to construct our corpus. Based on this, we initially developed a set of two logical subsets as set A and B. Set A, inspired by the remediation approach, includes papers from the Cognitive Theory of Multimedia Learning, borrowing elements, guidelines, and criteria from traditional and 2D digital media. Set B contained prominent review articles related to affordances in VR.

We performed forward and backward cross-citations across the sets A and B and engaged in iterative brainstorming within the research team. This helped us identify the papers and dimensions that formed the final corpus for the design space. This step was critical because VR offers affordances not characterized by traditional media, making it necessary to account for these unique aspects and their influence on component design in virtual environments. We stopped searching for new papers and dimensions once we reached saturation.

With the corpus finalized, the team conducted extensive brainstorming to determine the key design space dimensions. During this process, we began shaping the structure of the design space in a shared document. The sheet included category names, subcategories, definitions, possible values, and examples. In subsequent ideation sessions, we refined these dimensions, deciding which logically belonged in the VRLE design space. The final structure emerged after multiple iterations, with each version improving the clarity of definitions, the distinction between concepts, and the hierarchy of relationships.

6.1.2 Analysis of the Design Space

To analyze our design space, we employ the morphological analysis [100] approach, evaluating it through the lens of interaction model parameters proposed by Beaudouin-Lafon et al. [169], which include the following:

1. Descriptive power: the ability of the design space to describe a significant range of existing solutions;

2. Generative power: the ability to help designers create new designs and

3. Comparative or Evaluative power: the ability to help assess multiple design alternatives.

For this analysis, we employed a Systematic Literature Review (SLR) approach to comprehensively identify existing research and solutions related to VR-based learning environments. The overview of the SLR is illustrated in Figure 6.1.

Selection Rationale and Inclusion Criteria:

We used the Kitchenham and Charters guidelines [170] to conduct this SLR. We searched three major digital libraries in computer science and technology that incorporate works from the top venues for VR research: the ACM digital library, the IEEE Xplore digital library, and the Elsevier ScienceDirect library. Our choice of databases was guided by the

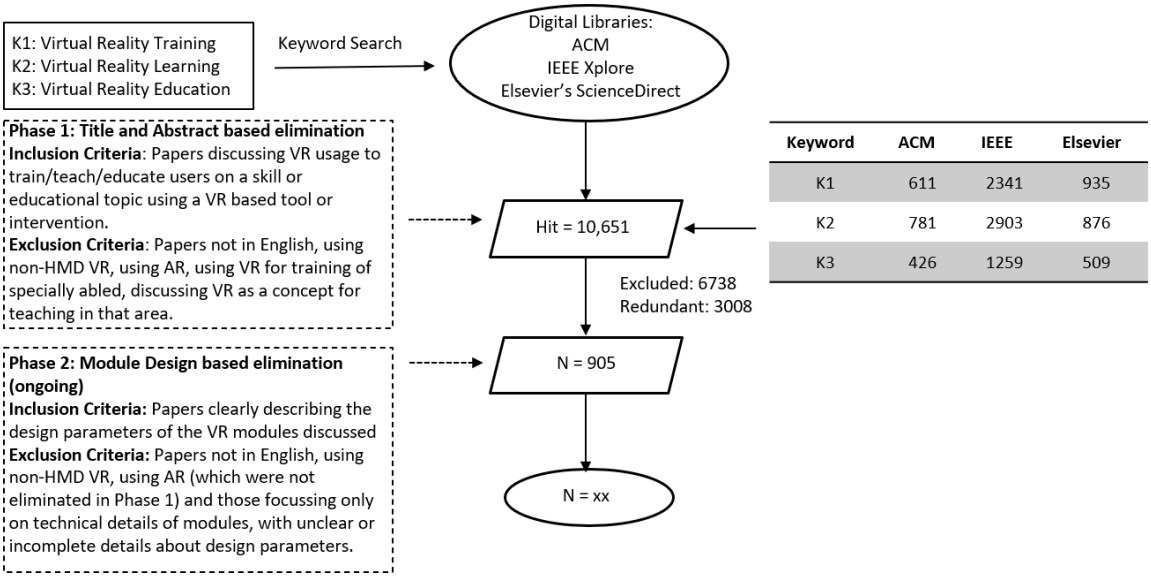


Figure 6.1: Overview of the systematic literature review (SLR) of VRLEs conducted to facilitate descriptive analysis of the design space.

fact that these repositories host the primary venues for publications in HCI, computer science, and immersive technologies. They index major conferences such as CHI, IEEE VR, ISMAR, and VRST, along with leading journals that consistently publish state-of-the-art research on VR interaction, learning technologies, and design frameworks. This focus does not mean, however, that our search was exhaustive or that we intended to capture only a single type of work. Rather, it reflects a deliberate scope aimed at ensuring both breadth and relevance within the field. While SpringerLink is also an important repository for capturing pedagogical and interdisciplinary perspectives on VRLEs, we excluded it from our search. Its limited support for advanced querying prevented us from applying consistent search strategies across all databases, which was essential for maintaining methodological rigor. We reviewed prior literature to compile a dictionary of key terms describing VR-based learning environments. Using this, we constructed cohesive search queries (e.g., "virtual reality training", "virtual reality learning", "virtual reality education") tailored to the advanced search functions of the selected digital libraries, ensuring comprehensive yet focused coverage. We collected articles published between 2015 and July 2025, corresponding to the third wave of VR that began with the launch of commercial initiatives by

major companies. [171]. The scope of the articles was limited to research articles published in conference proceedings and journals, which were accessible online and in English. The initial search queries yielded 10,651 articles across the three digital libraries, encompassing all combinations of our selected keywords. The SLR was conducted in two phases:

Phase 1: In the first phase, after retrieving all the articles containing the keywords in either their titles or abstracts from all three digital libraries, we determined the validity of each article (to be included in the morphological analysis) by reading its title and abstract. An article was included if it involved using VR to train, teach, or educate users on an educational topic or skill by implementing a VR-based tool or intervention. We have limited our survey to papers targeting VRLEs for formal and mainstream education and skill learning. We have, however, excluded literature targeting the learning or education of specially-abled students or rehabilitation-oriented training since particular affordances of virtual reality may not be feasible in those cases. We also excluded augmented (mixed) reality pedagogical environments as they overlay virtual elements onto real-world settings that vary across users. This introduces dynamic factors that shape learning by adding some affordances while limiting others. Non-English papers (missed in the initial filtration) were also eliminated from the survey as part of the exclusion criteria. After Phase 1 of filtering, 905 articles were retained for more detailed analysis in Phase 2.

Phase 2: In this phase, we thoroughly read the VRLE module implementation section of the papers identified from Phase 1. Only papers which comprehensively discussed the design aspects of the VR training module were included. Since our research is explicitly motivated by the design aspects of VR learning environments, our survey primarily focuses on research works that discuss the design aspects considered when developing these environments in detail. We had to exclude works focusing only on technical implementation details and discussing VR as a concept, deliberating its feasibility, advantages, and disadvantages in that educational area or studies evaluating the teaching module, since such works usually lacked design considerations and decisions. Apart from these, papers using

non-headset-based VR were eliminated, and multiple research works done on the exact VR simulation were entered into our Zwicky box only once.

6.2 Preliminary Findings

The synthesis has yielded eight core dimensions and two auxiliary dimensions which are further classified as representational and interaction dimensions along with emerging value sets for each dimension. The final set of papers resulting from the SLR are being categorized into a Zwicky box. The analysis to date has yielded a preliminary Zwicky box which illustrates how these dimensions interact to define a broad yet structured design space. In this thesis, we present this representative Zwicky box, with 15 papers for which we have completed both Phase 1 and Phase 2. We are currently continuing the Phase 2 process for the remaining papers identified from this SLR. Even in its early stages, the framework reveals recurring design tendencies and points to underexplored areas, indicating both the prevailing approaches currently favored in VRLEs and the potential for innovation in alternative interaction methods and representational forms.

6.2.1 The Design Space of VRLEs

In this section, we now explain in detail the key dimensions of the VRLE design space identified through a remediation-based approach, followed by snowballing and iterative discussions. We broadly classified these dimensions into two main categories: Representational Dimensions and Interaction Dimensions, which are detailed below in the following subsections. An overview of all the design space dimensions is illustrated in Figure 6.2

6.2.2 Representational Dimensions

The representational dimensions refer to parameters that define how various elements of the learning environment, such as instructional content, feedback, and virtual characters, are visually and experientially presented within the virtual world. Our design space comprises

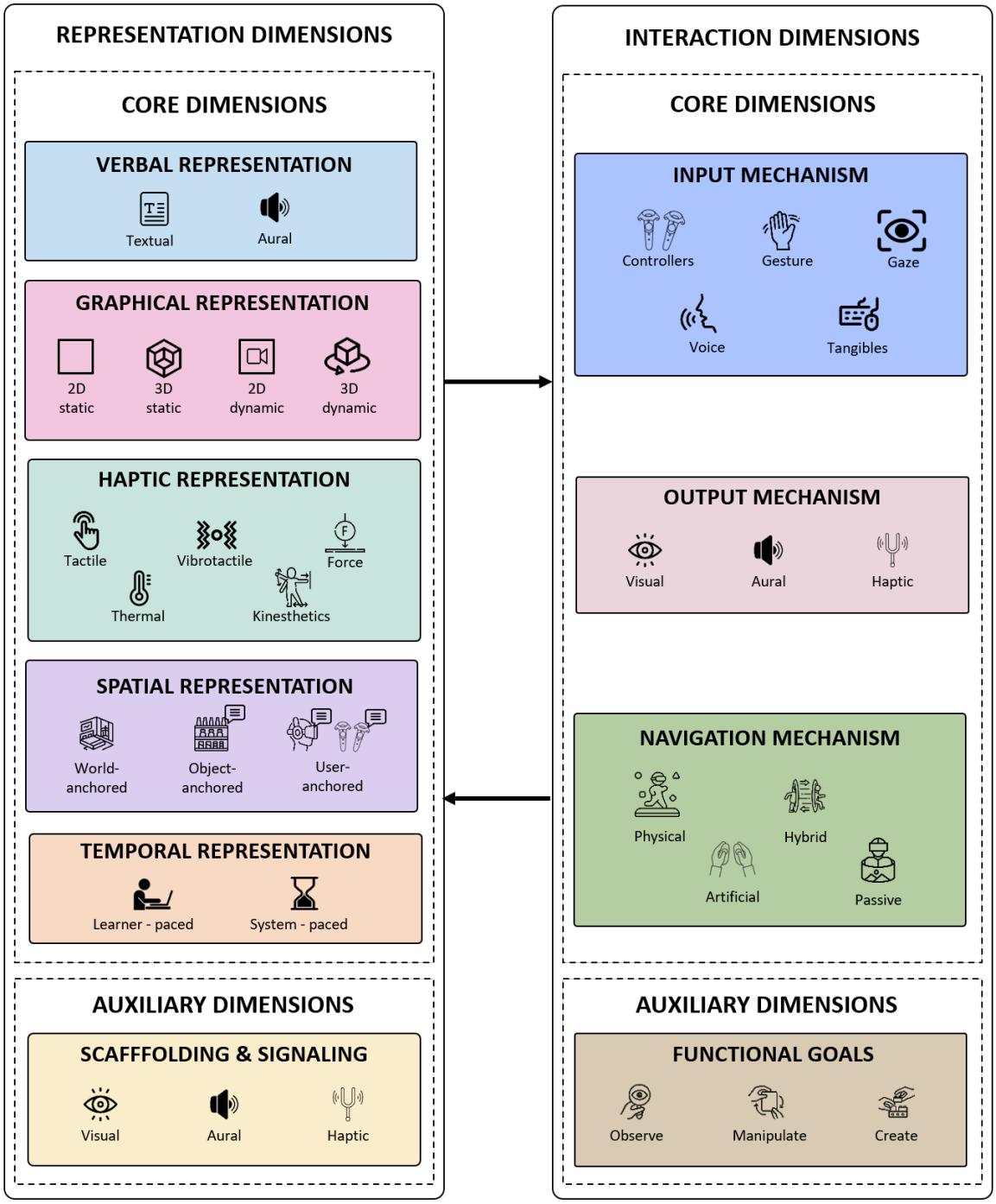


Figure 6.2: A design space for representation of VRLEs. The image has been designed using icons from flaticon, freepik and generative AI (https://www.flaticon.com/,https://www.freepik.com/).

six representational dimensions: five core and one auxiliary. The core dimensions are fundamental, as every learning element must be expressed through values defined along them. The auxiliary dimension is supplementary; its use depends on the context and the designer's intent. It can enrich a design scenario when included, but may also be omitted without undermining the essential representational structure of the learning environment. The five core representational dimensions include Verbal representation, Graphical representation, Haptic representation, Spatial representation, and Temporal representation, complemented by the auxiliary dimension of Scaffolding and cueing.

Verbal Representation

Verbal representation refers to the use of words to convey various elements within a learning environment. It is foundational for encoding core instructional elements such as conceptual content, procedural guidance, and formative feedback. Learning elements in VRLEs can be delivered verbally in two primary formats: textual and aural. The textual format facilitates the representation of elements in written form, whereas the aural format conveys these elements through auditory means.

As a core channel for delivering information, verbal representation communicates the intended learning elements and plays a key role in shaping how learners understand, process, and remember the content. When presented as a standalone modality, it predominantly engages the verbal processing channel of the learner's working memory. However, verbal representation drives dual-channel processing when combined with visuals, aligning with Mayer's Cognitive Theory of Multimedia Learning [14] that underscores the brain's limited capacity to process information.

Therefore, in VRLEs, which are more visually intensive (or reliant on visuals) than traditional learning environments, the careful design of verbal representation becomes even more critical, shaping cognitive load, learner engagement, and instructional coherence. This interplay can enhance learning outcomes provided the verbal input is effectively aligned

with other modalities to avoid redundancy or overload.

Graphical Representation

Graphical representation refers to using visuals to convey different elements within a learning environment. These visuals may serve as the primary content or as supportive aids that enhance the comprehension of accompanying verbal information. In the context of digital learning environments, particularly immersive VR-based settings, graphical representation plays a dual role. It not only supports the presentation of instructional content to enhance learning but also enables the visual depiction of real-world elements. These can include but are not limited to virtual characters to represent instructors or peer learners, physical environments (e.g., classrooms, labs, field sites), real-world tools and objects (e.g., lab equipment, instruments), abstract concepts (e.g., processes, models, or simulations), as well as scaffolds and interface elements that guide learners' interaction.

While 2D graphics have been used for a long time in traditional multimedia learning environments, VR expands these possibilities by affording the use of 3D graphical representations. These 3D visuals enable more realistic and spatially immersive depictions of learning elements, allowing learners to view objects from multiple vantage points, navigate around them, and manipulate them directly. This contrasts with non-VR environments, where visuals are typically limited to fixed, locked camera angles and static perspectives, thereby restricting the depth of interaction and spatial understanding.

Graphical representations can further be categorized based on their static or dynamic nature. Static representations include photos, drawings, maps, charts, figures, and tables in 2D environments, extending to 3D models in immersive VR settings. On the other hand, dynamic representations involve movement over time, ranging from short video clips, GIFs, and animations in 2D formats to fully animated 3D objects and scenes in VR. These dynamic visuals can enhance learner engagement and understanding by depicting processes, transformations, or behaviours that unfold progressively.

The dimensionality and interactivity afforded by VR have the potential to enhance engagement and foster a heightened sense of presence and realism in learning. However, heightened visual complexity and dynamism impose considerable computational overhead and necessitate advanced design expertise. Thus, making deliberate decisions about which elements of the learning environment require which level of graphical representation becomes crucial, carefully balancing the trade-offs between realism, learner experience, and logistical feasibility.

Haptic Representation

Compared to traditional 2D multimedia learning environments, one of the distinguishing affordances of VR is its ability to deliver sensory feedback through haptic interactions. While haptics is traditionally strongly associated with interaction, we position it as a representational dimension of VRLEs, owing to its capability for encoding and conveying various instructional elements within a VR learning environment. They may serve as feedback mechanisms, providing confirmation or correction in response to user actions, or act as attentional scaffolds, guiding user focus, confirming selections, or indicating specific events. In more advanced implementations, haptic representations can be simulative, conveying physical properties such as resistance, pressure, or texture to emulate real-world phenomena. It can also take on a metaphoric function, representing abstract or emotional states, for example, a pulsing vibration to signal stress or urgency. Additionally, haptic cues can be employed for spatial orientation and navigation, such as directional vibrations that assist users in locating objects or navigating the environment. Therefore, haptic representations extend beyond their conventional role as system-level response mechanisms in pedagogically structured VR learning environments. They also function as a representational channel that conveys, simulates, or signals instructional meaning, enhancing the learner's perception and understanding of key instructional elements.

Haptic representations in VRLEs can be realized through diverse sensory modalities.

Tactile feedback encompasses surface-level, localized sensations such as pressure or pokes. Vibrotactile feedback involves the delivery of vibrations via devices such as controllers or wristbands. Force feedback simulates resistance or weight through mechanisms including robotic arms or exoskeletons. Thermal feedback conveys temperature-based cues, such as heat or cold, to replicate environmental conditions or affective states. Kinesthetic feedback engages the learner's perception of movement and muscle tension, thereby supporting tasks that require spatial orientation or fine motor coordination.

Collectively, these haptic modalities facilitate more immersive and embodied learning experiences within VR. Both the modality of haptic representations, whether physical, symbolic, emotional, or attentional, and their specific forms, such as vibrotactile, force-based, thermal, or kinesthetic, influence how learners perceive, interpret, and respond to content in the virtual environment. Each modality supports distinct technological or design strategies for delivering haptic input and plays a pivotal role in shaping learner engagement, immersion, and the overall effectiveness of instructional delivery. Consequently, haptic representation constitutes a critical dimension of the VRLE design space.

Spatial Representation

Spatial representation refers to how different learning environment elements, such as verbal content (e.g., textual information), associated graphics, scaffolds, feedback, and virtual characters, are positioned within the virtual space. In VRLEs, the spatial arrangement of these elements plays a crucial role in shaping the learner's experience, guiding attention, and supporting cognitive processing by leveraging the affordances of 3D environments. Unlike 2D learning environments, VR enables objects to be positioned freely within three-dimensional space, with any orientation, and experienced from a first-person perspective [172]. Leveraging these spatial affordances, learning elements can be represented through three primary spatial configurations: world-anchored, user-anchored, and object-anchored. In a world-anchored configuration, elements are fixed to specific locations

within the virtual environment. In a user-anchored configuration, elements are tethered to the user (commonly via the head-mounted display or controllers). In an object-anchored configuration, elements are attached to the object of interest within the learning scenario.

While the spatial flexibility enabled by VR offers a far richer set of representational possibilities, it also introduces new challenges. As learners navigate freely within immersive scenes populated by multiple instructional elements, strategic spatial placement becomes essential to prevent visual clutter, obstruction, or the risk of overlapped or overlooked key content. Therefore, spatial representation of learning elements emerges as a pivotal design consideration, as it fundamentally shapes the degree of immersion, the facilitation of intuitive interaction and navigation, cognitive load management, and, by extension, the overall effectiveness of the learning experience.

Temporal Representation

Temporal representation refers to the control and duration of learning content presentation within a VRLE. It determines whether the content is delivered at a fixed pace (system-paced) or adapted to the learner's interaction. In a system-paced format, the learner has no control over the timing, and content is displayed for a predetermined duration set by the system. In contrast, a learner-paced (also referred to as user-paced or self-paced) format allows the learner to influence the progression of the content. This control can be explicit, where users are provided with navigation tools (e.g., buttons, menus) to proceed at their own pace, or implicit, where the system adapts the pacing automatically by tracking learner behaviour and performance during specific activities.

While the core parameters of temporal representation remain similar across VR and 2D screen-based learning environments, their role becomes especially critical in VRLEs. Unlike 2D settings, navigating and processing information in immersive 3D environments demands more cognitive and physical effort, often requiring additional time for exploration, interaction, and comprehension. As such, carefully considering the pacing of learning con-

tent, whether system-controlled or learner-controlled, is vital to ensuring effective learning experiences in VR. This makes temporal representation a key dimension in the design space of VRLEs, directly influencing learner engagement, comprehension, and cognitive load.

Scaffolding and Signaling

Scaffolding (or cueing) refers to attention-directing cues embedded within the learning content to guide learners' focus and support their interaction with the environment. Unlike the core representational dimensions, scaffolding is not always necessary in a VRLE; however, when present, it significantly enhances learners' ability to navigate, interact, and make sense of the environment. Scaffolding can take multiple forms, such as visual cues (e.g., highlights, glowing outlines, animation pulses), aural cues (e.g., beeps, tonal shifts, spoken prompts), or haptic cues (e.g., vibrations, pulse feedback). While often subtle, these cues are powerful attentional affordances that reduce cognitive load and help learners prioritize relevant information.

In the context of VR, scaffolding becomes particularly important because of the unique spatial and interactive affordances of 3D environments. Learning elements may be widely dispersed within the virtual space, and learners have the freedom to explore and navigate in multiple directions. This freedom, while beneficial, can also lead to disorientation or missed information. Scaffolding or signalling mechanisms can therefore act as guidance systems, ensuring that learners remain oriented, attend to critical information, and engage with the intended learning pathway without being overwhelmed by the richness of the environment.

6.2.3 Interaction Dimensions

The Interaction dimensions define how learners engage with and manipulate the VRLE environment and how the system responds to their actions. These mechanisms enable learners to shape their experiences actively, positioning them as participants in the learning process

rather than passive recipients of information. The design space incorporates three core interaction dimensions and one auxiliary dimension. The core interaction dimensions include - Input mechanism, Output mechanism, and Navigation mechanism, complemented by the auxiliary dimension, which is the Functional goal.

Input Mechanism

In the context of VRLEs, input mechanisms refer to the modalities through which learners actively engage with the virtual environment by providing inputs to the system. These mechanisms define how users communicate intentions, perform actions, and influence the virtual world. By enabling direct and purposeful interaction, they facilitate meaningful engagement with learning tasks, foster a sense of agency, and enhance the overall effectiveness of the instructional experience.

VR supports a broad spectrum of input mechanisms, including built-in controllers bundled with commercial headsets, hand gesture recognition, gaze-based selection, and voice commands. Recent research has expanded these capabilities through tangible interfaces, which use physical objects or virtual counterparts replicating real-world properties to enhance realism and enrich user interaction. For instance, devices such as the PHANTOM [173] haptic interface and LEGO-based toolkits [174] demonstrate how tangible interaction can deepen engagement by allowing users to manipulate and explore virtual environments physically. Although controllers can be considered a type of tangible interface, they are treated as a separate dimension in this design space. This distinction is intentional, as merging controllers and tangible interfaces into a single category would obscure the distinction between a well-established, frequently used interaction mechanism and a relatively recent, less common approach. In practice, such aggregation could misrepresent the actual adoption patterns in the design space.

Input mechanisms constitute a critical dimension of the VRLE design space, as their configuration directly shapes user experience, engagement, and learning outcomes. Poorly

matched, overly complex, or unfamiliar interaction modalities can shift cognitive resources away from the intended learning tasks, diminishing educational effectiveness. This effect was evident in Chapter 5 of this thesis, where a substantial portion of the negative cognitive load reported by participants stemmed from the interaction demands of the tasks themselves. Therefore, careful selection and design of interaction mechanisms are essential to ensure that they facilitate, rather than hinder, the learning process.

Output Mechanism

Output mechanisms specify how the system responds to user actions and delivers feedback within VRLEs. They can encompass confirmatory feedback, acknowledging that an action has occurred; corrective feedback, which signals whether the action was accurate or aligned with task requirements; and directive feedback, which nudges learners toward more effective strategies or behaviours. Together, these mechanisms provide learners with ongoing information about their performance, promote self-regulation, and scaffold the learning process. Output mechanisms play a critical role in sustaining engagement and fostering effective learning outcomes by structuring the dialogue between user and system.

Output mechanisms in a VRLE can be delivered to the learner through visual, auditory, or haptic channels. Visual outputs may include verbal elements such as on-screen text or symbolic indicators and graphical cues such as highlights, colour changes, or animations. Auditory outputs include speech, instructional narration, or non-verbal signals such as beeps, tones, or spatialized sounds. Haptic feedback, as outlined in the haptic representation dimension, encompasses many modalities, including vibrations, force feedback, and kinesthetic resistance.

Collectively, by responding to user actions and delivering feedback at multiple levels, multimodal outputs play a vital role in guiding learners, sustaining engagement, and reinforcing a sense of presence within the virtual environment. When poorly designed or absent altogether, learners may feel disoriented, uncertain about how to proceed, and about

their progress, which can disrupt the learning flow and hinder knowledge acquisition. This challenge becomes particularly significant in VRLEs, which are frequently designed as isolated and self-directed, lacking the presence of a real-world instructor or relying solely on virtual agents for guidance.

Navigation Mechanism

Navigation mechanisms define how learners move through and explore the virtual learning environment. When effectively designed, they cultivate spatial immersion and control by facilitating exploration and supporting task performance. They also strengthen presence, advancing learner engagement and effective learning.

VR supports a wide range of locomotion and navigation mechanisms, each encompassing a variety of techniques. Physical locomotion relies on the user's real-world body movements to control motion in the virtual space. This can involve real walking within a tracked area or room-scale movement inside a predefined boundary. Alternatives include walking in place, where stepping or jogging motions simulate forward movement, and arm-swinging gestures, where hand motion mimics walking. Device-based methods, such as omnidirectional treadmills or VR shoes, enable walking in place while virtually translating the motion. Artificial locomotion relies on input devices rather than direct physical movement. Standard techniques include joystick or thumbstick controls for continuous motion and rotation, teleportation for instant jumps to new locations, and dash or blink movements for rapid short-range transitions with a fade effect. Other approaches include flying or gliding for unrestricted 3D movement, target-based navigation to reach specific points, and gaze-directed movement that advances the user in the direction they are looking. Hybrid locomotion combines physical and artificial methods to extend movement possibilities. Examples include redirected walking, where visual feedback is subtly altered to reuse limited physical space; motion scaling, which maps small real-world movements to larger virtual distances; and assisted walking, where users move physically but the system adjusts

their direction or speed. Passive or automatic locomotion removes direct user control and moves the user through the environment. Approaches include on-rails navigation, where users follow a predetermined path like a guided tour; auto-walk to target, where the system transports them to a selected object or location; and narrative-driven transitions, where movement is built into the unfolding story or scene change. We organize the design space into four broad navigation mechanisms: physical, artificial, hybrid, and passive, to provide a clearer and more comprehensible representation. Grouping techniques into these categories keeps the analysis structured and accessible, whereas listing each locomotion technique individually would have resulted in a fragmented and less interpretable design space.

In the context of VRLEs, the choice of locomotion technique must balance immersion, physical effort, comfort, and cognitive load, as navigation directly shapes learners' engagement with the environment and the overall quality of their learning experience. If locomotion is inefficient or poorly matched, it can draw attention away from instructional content, disrupt presence, and hinder the achievement of educational objectives. Thus, selecting an appropriate locomotion method is not merely a technical consideration but a pedagogical one, ensuring learners can move through the environment seamlessly, without discomfort, disorientation, or unnecessary cognitive strain.

Functional Goals

The functional goal dimension defines the learner's underlying purpose for interacting with elements of the virtual environment. These goals determine whether learners acquire information, practice a skill, test their understanding, or explore freely. By clarifying intent, functional goals shape the nature of learner actions and influence how the system scaffolds their educational objectives. Therefore, they help guide the design of input mechanisms based on whether interactions should prioritize precision, speed, or creativity and determine the most appropriate feedback type, such as corrective, supportive, or exploratory

cues.

The values of this dimension are organized into three core categories: observe, manipulate, and create. These categories capture the fundamental purposes of interaction within a VRLE. Observe refers to interactions aimed at perceiving or retrieving information, such as exploring the environment, consuming content, examining objects, or attending to visual or auditory cues. Manipulation involves altering or controlling elements of the environment, for example, by moving, rotating, or adjusting objects to achieve a learning goal. Create encompasses activities where learners generate new artefacts, assemble structures, or ideas within the environment.

Defining clear interaction goals ensures that learner actions remain purposeful, aligned with educational objectives, and unburdened by unnecessary complexity that might hinder engagement or cognitive processing. In VRLE design, such goals function as a guiding framework for selecting and integrating interaction techniques that enhance both usability and learning outcomes. As such, interaction goals are central to shaping and structuring the overall learning experience.

6.2.4 Work in progress-Design Space Analysis

Phase 1 of the systematic literature review (SLR) identified a corpus of 905 publications. In Phase 2, this corpus is being systematically filtered using the predefined inclusion and exclusion criteria, after which the eligible studies are represented within a Zwicky box through morphological analysis. The Zwicky box operationalizes the three principal virtues of design spaces — descriptive, generative, and comparative capabilities. We do this by mapping the representational and interaction dimensions identified in each paper against the learning objectives, with the latter categorized according to Bloom's Taxonomy [175]. Bloom's Taxonomy is utilized as a primary axis in the morphological framework to enable a deeper analytical understanding of how these dimensions ground in educational contexts, thereby reinforcing the validity and relevance of their inclusion in the VRLE design space.

Figure 6.3 presents an illustrative subset comprising an initial set of fully analyzed studies mapped within the Zwicky box; ongoing work is focused on completing this mapping for the remaining studies from the SLR corpus.

Descriptive Analysis of VRLE Design Space	Representation Dimensions																			Interaction Dimensions														Learning Goal
	Verbal Representation		Graphical Representation				Haptic Representation					Spatial Representation			Temporal Representation		Scaffolding & Cueing			Input Mechanism					Output Mechanism			Navigation Mechanism				Interaction Goal			
	Textual	Aural	2D static	2D dynamic	3D static	3D dynamic	Tactile	Vibrotactile	Force	Thermal	Kinesthetic	World-anchored	User-anchored	Object-anchored	System-paced	User-paced	Visual	Aural	Haptic	Controller	Gaze	Gesture	Tangibles	Voice	Visual	Aural	Haptic	Physical	Artificial	Hybrid	Passive	Observe	Manipulate	Construct	
Design Virtual Reality Simulation System for Epidemic (Covid-19) Education to Public	■		■		■															■			■		■							■		Remember Understand
Getting Up Your Nose: A Virtual Reality Education Tool for Nasal Cavity Anatomy		■			■	■														■								■						Remember Understand
Learning by Doing: Evaluation of an Educational VR Application for the Care of Schizophrenic Patients	■	■				■										■				■												■			Understand Apply
Virtual Simulation for Scoliosis Surgery	■	■	■	■	■															■		■											■		Understand Apply
Learning Success in Immersive Virtual Reality Training Environments: Practical Evidence from Automotive Assembly	■	■	■		■							■				■	■	■		■					■	■	■						■		Remember Understand Apply
LearnIoTVR: An End-to-End Virtual Reality Environment Providing Authentic Learning Experiences for Internet of Things	■		■		■							■		■		■				■								■	■				■	■	Understand Apply Create
Design and Evaluation of a VR Training Simulation for Pump Maintenance	■	■		■	■		■					■				■	■	■	■	■													■		Remember Understand Apply
Words in Kitchen: An Instance of Leveraging Virtual Reality Technology to Learn Vocabulary	■	■			■							■				■				■												■			Remember Understand
AirwayVR: Learning Endotracheal Intubation in Virtual Reality	■				■	■	■													■							■					■	■		Remember Understand Apply
An Immersive Virtual Reality Game Designed to Promote Learning Engagement and Flow	■		■		■							■				■	■			■					■			■				■	■		Remember
Virtual Reality for Immersive Learning in Art History	■		■										■			■				■										■			■			Remember Understand
Assessing the Learning of Folk Dance Movements Using Immersive Virtual Reality		■				■						■				■				■					■			■				■			Understand Apply

Figure 6.3: Zwicky box representation (preliminary) using morphological analysis to represent descriptive and generative capability of the design space.

At the conclusion of this analysis, the extent to which the identified dimensions can account for all papers from the SLR will serve as an indicator of the descriptive virtue of the design space, reflecting its ability to systematically represent the breadth of existing work. Areas within the Zwicky box that are sparsely populated or entirely unrepresented will correspond to its generative virtue, highlighting unexplored configurations and po-

tential avenues for innovation. These gaps can inform designers about opportunities to experiment with novel ideas, parameter combinations, and design strategies. Furthermore, the Zwicky box will facilitate the comparative virtue of the design space by providing a consolidated overview of existing comparisons across different dimensional values. This enables designers to make evidence-based design decisions and allows researchers to identify missing comparative analyses, thereby guiding future empirical investigations into the feasibility and effectiveness of specific dimensional configurations in varied VRLE contexts.

6.3 Steps Ahead

Completing the design space mapping to its intended scope requires a deeper iterative process, including expansion of the literature corpus, expert validation workshops, and application to case study environments. Given the concurrent demands of large-scale empirical data collection and analysis, these phases could not be undertaken within the time frame of the doctoral work. The current state of the study is presented as a well-grounded foundation, poised to support and inform its subsequent development and refinement. Building on the groundwork established here, the next steps include completing the analysis of the SLR corpus, conducting expert validation sessions to refine dimensions and value sets and applying the design space to analyze and compare real-world VRLE deployments.

These steps will culminate in a standalone publication aimed at the learning sciences and HCI communities, contributing both a methodological framework and a synthesized knowledge base to the field. Even in its present form, the study offers a structured vocabulary and preliminary analytical lens for discussing VRLE design. These outputs can inform the interpretation of results from earlier chapters and support more targeted design recommendations. Moreover, the current mapping surfaces potential gaps in existing literature, which directly inform a part of the future research agenda outlined in the next chapter.

6.4 Key Contributions and Current Status

This work, upon completion, aims to make the following contributions to the existing literature on Virtual Reality Learning Environments (VRLEs):

- First, it proposes a structured vocabulary and a preliminary analytical lens for systematically describing VRLE design. This contribution enables designers and researchers to classify and articulate existing and prospective VRLE design choices, and to express design intent at a strategic level. This component of the work is complete and is presented in Section 6.2.1 of this chapter.

- Second, this vocabulary is being used to systematically identify gaps within the existing literature. In doing so, it helps surface underutilized VR affordances that merit greater research attention and points to potential directions for investigating the underlying reasons for these gaps. This contribution is discussed in Section 6.2.2 of this chapter and is currently in progress. It will be completed with the conclusion of Phase 2 of the systematic literature review.

- Finally, this work aims to enable the identification of meaningful combinations of design parameters that should be systematically evaluated during the VRLE design process. This forms the foundation for developing targeted design recommendations, principles, and, ultimately, a comprehensive framework for VRLE design. This constitutes future work and is discussed in the next chapter.

6.5 Limitations

While the present work offers a comprehensive and structured design space for VRLEs, certain inherent limitations remain, pointing toward opportunities for future research. A design space can never be entirely exhaustive, as new technologies, design innovations, and pedagogical approaches continuously emerge, necessitating ongoing expansion and

refinement. We also acknowledge that some dimensions inevitably exhibit overlapping characteristics. For example, during our analysis, we observed partial overlap between the Scaffolding and Signalling and the Output Mechanism dimension, particularly in cases involving narrative feedback. Although complete separation of these dimensions is not feasible without excluding meaningful instances, iterative refinement can help maximize mutual exclusivity among dimensions and their value sets.

CHAPTER 7
CONCLUSION & FUTURE WORK

This dissertation constitutes an initial yet significant step toward the systematic design of VRLEs that align with pedagogical objectives, enhance learning outcomes, and facilitate sustained integration into mainstream educational practice. Drawing on a mixed-methods approach comprising empirical evaluation, a long-term integration study, and a systematic literature review, it delineates a design and adoption landscape for VRLEs firmly grounded in pedagogical and design theory. Empirical insights are presented through two case studies that examine the influence of two critical affordances of VR, verbal and spatial, on diverse learning outcomes, leading to concrete design implications and recommendations for the representation of learning elements. By analyzing factual, conceptual, and procedural domains, this work highlights how VR's unique strengths in facilitating procedural learning fundamentally reshape the cognitive demands of different content types, underscoring the need for tailored design approaches. Beyond these findings, this research offers key considerations and best practices for adopting VRLEs in situ. It also advances the broader HCI discourse by proposing a foundational design framework that guides VRLE design, identifies gaps in the use of VR affordances, and informs future research and practice. The framework supports practitioners in the principled design of VRLEs and enables researchers to identify gaps in the use of VR affordances, understand their underlying causes, and develop guidelines for the effective and sustainable design of VR learning environments.

The first study in Chapter 3 examined the impact of different spatial representations of learning elements in VRLEs, addressing an affordance that had not previously been investigated in a pedagogical context. Although learning outcomes and cognitive load did not significantly differ across the four spatial placements, the object-anchored placement outperformed all other configurations in user experience, driven by its higher perceived

attractiveness, stimulation, and novelty, also making it one of the most preferred spatial representations among users. User-anchored spatial representation was also ranked equally high in terms of participant preferences. However, user preferences shifted when contextual factors—specifically, the type of learning content—were considered. Head-mounted (HMD-based) placements were perceived as more convenient for factual and conceptual topics (such as history and biology), but became obstructive for procedural tasks, for which controller-anchored placement emerged as the preferred alternative. While our study focused on a single such contextual variable (content type), these patterns underscore the value of spatial design choices and point to promising directions for future research across diverse learners and contexts as VR integration in education grows.

The study in Chapter 4 evaluated another core affordance of learning environments, verbal representation, in VR. This study examined how modality and its redundant combinations interact with content type to shape cognitive load and user experience in immersive VR learning. Our findings, informed by objective outcomes, self-reports, interviews, and physiological data, indicate that redundant modalities are particularly effective for procedural content. Concise redundancy consistently reduces extraneous cognitive load and is preferred by learners, whereas audio-only delivery imposes the highest cognitive load. This work can further be extended to upcoming higher levels /complexities of modalities like human avatars etc. However, in this work we limited ourselves to the two modalities to ensure a controllable set of study design parameters.

The research work in Chapter 5 offers a grounded understanding of the sustained adoption of VR in educational settings by examining its deployment over a semester-long undergraduate course. The exploratory findings from this study call for a recalibration of how VR is designed and integrated into learning ecosystems. By surfacing students' initial motivations and hesitations, it reveals how meaningful engagement hinges on fulfilling autonomy, competence, relatedness and novelty needs, often partially met in traditional learning environments. Building on learning theories, the work proposes considerations

and best practices for integrating VR into education in sustainable, student-centered, and contextually responsive ways.

Finally, the research in Chapter 6 maps the design space of VRLEs, identifying key dimensions and their associated values, organized into representational and interaction dimensions. This work contributes by synthesizing the design space and analyzing it through descriptive, generative, and comparative lenses. It offers a foundational framework that guides designers in making informed choices across design dimensions and supports researchers in evaluating and advancing those choices.

7.0.1 Overarching Contributions and Key Insights

The collective body of this dissertation advances overarching contributions that transcend the individual case studies, offering significant theoretical and conceptual insights to the field of HCI. Firstly, this thesis proposes a structured design space that categorizes the dimensions of VRLEs into representational and interaction dimensions. By systematizing the design elements of VRLEs, the framework advances HCI by offering a principled lens to analyze, compare, and extend interaction design in immersive contexts. For VR research, it provides a conceptual map that highlights underexplored areas and uncovers opportunities for innovation in VR-based educational technologies. Within learning sciences, it serves as a practical tool for designing pedagogically aligned VR experiences, guiding practitioners to make informed, evidence-based design decisions, and enabling researchers to critically evaluate and refine how VR affordances support different kinds of learning. In this way, the framework bridges theory and practice, advancing both conceptual understanding and actionable guidance for the effectual design of VR in education.

Secondly, through exemplary case studies, this thesis demonstrates how the design space can be used as a comparative tool to generate empirical insights into how different VR affordances influence learning outcomes and learner experiences. These insights reveal how such effects are moderated by factors such as content type and learner expertise.

By systematically comparing the values of design dimensions across a range of contexts, this work advances HCI and VR research with evidence-driven analyses and provides the learning sciences with actionable guidelines for designing effective and context-sensitive VRLEs.

Finally, this thesis offers key considerations and best practices for the sustained adoption of VRLEs into mainstream curricula. By synthesizing empirical findings and design insights, it highlights the infrastructural, pedagogical, and experiential factors necessary to support long-term use beyond experimental settings. This contribution advances HCI by grounding design frameworks in real-world adoption contexts, informs VR research by addressing challenges of scalability and sustainability, and enriches the learning sciences by providing practical strategies for embedding immersive technologies into everyday teaching and training practices.

Collectively, these contributions lay a strong foundation for advancing research at the intersection of HCI, VR, and learning, while simultaneously revealing several opportunities for further advancement. Building on the findings and insights of this dissertation, the following section outlines three promising directions for future research that build directly on the findings of this dissertation.

7.1 Future Research Directions

7.1.1 Devising Guidelines and Frameworks for VRLE Design

Our preliminary design space analysis highlights significant gaps in the use of design dimension values. At the same time, our empirical findings reveal a lack of comparative analysis of these dimensions across varying contexts. These gaps present valuable opportunities for future research. By addressing these gaps, researchers can conduct studies that explore how different design dimensions and contextual factors influence the effectiveness of VRLEs. This research could lead to developing evidence-based guidelines for making optimal design choices across different VRLE dimensions and conditions. Such work

would support the development of practical design guidelines and lay the groundwork for a comprehensive framework that VRLE designers can draw upon to achieve optimal outcomes, tailored to specific educational objectives and contexts.

7.1.2 Exploring the Potential of AI and LLMs in VR-Based Education

A recurring gap identified throughout my research (Chapters 4 and 5) is the need for dynamic and adaptive VRLEs that promote effective learning and maintain student engagement and interest. As research in artificial intelligence (AI) continues to advance, developing VRLEs capable of adapting to individual users' needs and progress has become increasingly feasible. It will be particularly valuable to explore how AI technologies, such as Large Language Models (LLMs), can be integrated into VRLEs to enhance the learning experience [160, 159]. For instance, incorporating AI-driven mentors or instructors within VR environments could provide real-time guidance to students, helping them navigate challenges and reinforcing their learning process. Additionally, using smart VR environments could enable the implementation of VR-based assessments, allowing for more immersive and accurate evaluations of students' skills and progress within the virtual setting. Finally, advancing current static VR learning environments into dynamic and adaptive systems, capable of modulating difficulty, pacing, and progression while minimizing redundancy, would enhance their practicality and foster the sustained integration of VRLEs within educational contexts. These developments can significantly enhance the effectiveness and user experience of VRLEs, paving the way for more personalized, adaptive, and engaging learning environments.

7.1.3 Collaborative VRLEs

In my dissertation research, I intentionally focused on single-user VRLEs as an initial exploration into the design and adoption of VRLEs. This approach was foundational in understanding how VRLEs can be optimized for individual learning experiences. Moving

forward, this research can be extended to explore multi-user VRLEs, an area that has gained significant attention with the increasing accessibility of VR headsets, decreasing hardware costs, and advancements in development technologies.

Social collaboration within VR environments is rapidly emerging as a key area of interest, particularly in the educational context [155, 176]. The shift from single-user to multi-user VRLEs introduces new challenges and opportunities. The design will need to accommodate various types of collaboration, such as peer-to-peer student interaction, student-instructor collaboration, and group learning experiences. It will also require rethinking hardware configurations, software development, and user interaction models. Evaluating how these collaborative dynamics function in VR, and how they can be optimized for diverse learning goals, will be crucial to the next phase of VRLE research and development. Additionally, factors such as network stability, user interface design, and the scalability of VRLEs for larger groups will need to be carefully studied to ensure effective, seamless, and engaging multi-user experiences.

7.2 Concluding Remarks

This dissertation set out to advance the understanding and design of VRLEs by investigating their affordances, cognitive implications, and pedagogical potential. Through a series of empirical studies and the development of a structured design space, it has contributed both conceptual clarity and actionable insights to the fields of HCI, VR, and educational technology. The proposed design space, comparative analyses, and best practices provide a foundation for designing more effective, sustainable, and learner-centered VRLEs.

Looking forward, the identified directions for future work: developing refined guidelines and frameworks, integrating AI and large language models into VR-based education, and enabling collaborative VRLEs, signal a fertile agenda for extending this research. Together, these avenues promise to deepen our understanding of immersive learning and ensure that VR can be meaningfully embedded in mainstream curricula.

In conclusion, this thesis contributes to the ongoing discourse on immersive learning technologies while also laying the groundwork for future technological advancements that may fundamentally transform the ways knowledge is created, shared, and experienced.

Appendices

APPENDIX A

COURSE WORK

Table A.1: Courses Summary

Course ID	Course Name	Credits	Grade	Instructor
CSE501	Designing Human-Centered Systems	4	A-	Prof. Ponnurangam Kumaraguru
CSE535	Mobile Computing	4	B	Prof. Pushpendra Singh
CSE790	Independent Study	4	A	Prof. Ponnurangam Kumaraguru
ENG599	Research Methods	2	A-	Prof. Anubha Gupta
DES513	Wearable Applications, Research, Devices, Interactions	4	A-	Dr. Aman Parnami
DES518	Introduction to Motion Graphics	4	A-	Mr. Anoop Ratn
CSE790	Independent Project	4	A	Dr. Aman Parnami
DES506	Advanced Topics in Human Centered Computing	4	A+	Prof. Pushpendra Singh
DES519	Design of Interactive Systems	4	A-	Dr. Aman Parnami

APPENDIX B

THESIS PUBLICATIONS

- **Manshul Belani**, Harshvardhan Singh, Aman Parnami and Pushpendra Singh. 2023. Investigating Spatial Representation of Learning Content in Virtual Reality Learning Environments. 2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR).
- **Manshul Belani** and Aman Parnami. 2020. Augmented reality for vocational education training in K12 classrooms. 2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), pp. 317-320.
- **Manshul Belani**. 2020. Evaluating virtual reality as a medium for vocational skill training. Extended abstracts of the 2020 CHI conference on human factors in computing systems, pp. 1-8.

APPENDIX C

OTHER PUBLICATIONS

- Sara Moin, **Manshul Belani**, Pragya Singh, Nishtha Phutela and Pushpendra Singh. "But I Won't Say That It was Bad Seeing a Real Vagina": Understanding Perspective towards Learning Sensitive-Critical Health Topic. Accepted at 2025 CHI Conference on Human Factors in Computing Systems (CHI 2025).

- Akash Chaudhary, **Manshul Belani**, Naman Maheshwari and Aman Parnami. 2021. Verbose: Designing A Context-based Educational System for Improving Communicative Expressions. Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction, MobileHCI 2021, 13 pages.

- Akshansh Chahal, **Manshul Belani**, Akashdeep Bansal, Neha Jadhav, and Meenakshi Balakrishnan. Template Based Approach for Augmenting Image Descriptions. Computers Helping People with Special Needs: 16th International Conference, ICCHP 2018, Proceedings, Part I 16, pp. 104-112.

- **Manshul Belani**, Meenakshi Balakrishnan, Dinesh Kaushal and Manish Agrawal. 2018. DescribeIt: Making Web Images More Accessible with NVDA. Presented at CSUN Assistive Technology Conference, 2018.

- Siddhartha Gupta, **Manshul Belani**, Dinesh Kaushal and Meenakshi Balakrishnan. 2016. Microsoft Excel Chart Accessibility: An Affordable and Effective Solution. In Proceedings of the Digitization and E-Inclusion in Mathematics and Science 2016.

- Nitin Sharma, **Manshul Belani** and Indu Chawla. A Cost Efficient Solution for Surface Technology with Mobile Connect. International Journal of Modern Education and Computer Science, Volume 5, Issue 9.

APPENDIX D

QUESTIONNAIRES FOR CHAPTER 3 AND 4

This appendix contains the questionnaires used pre and post intervention in Chapters 3 and 4. These supplementary materials include the following documents:

a. Consent form, Demographics, Familiarity ratings, Knowledge Gain and Workload Questionnaire for Spatial representation study (Ch 3).

b. Consent form, Demographics, Familiarity Ratings and Knowledge Gain questionnaire for the follow-up spatial representation study (Ch 3).

c. Pre-intervention questionnaire (including consent form) for Multimodality evaluation study (Ch 4).

d. Post-intervention questionnaire for Multimodality evaluation study (Ch 4).

Spatial Representation of Learning Content in VR

Consent Form

Principal Investigator: Prof Pushpendra Singh
Affiliated Interviewers: Ms. Manshul Belani

Neither IIIT Delhi, nor these researchers will receive any financial benefit based on the study results. This study has been approved by IIIT Delhi's Institutional Review Board (IRB).

Purpose of the study: The researchers want to evaluate the effects of different spatial representations of learning content in VR education environments.

Interview procedure: You will be asked about your overall experience with the system.

Risks / discomforts / costs: The experience is expected to be inherently interesting and a generally positive experience. There will be no (other) cost to participating other than your time.

Research benefits: The specific objective of the study is to understand the effect of various placements of learning content in VR learning environments on learning metrics. Through a prototype learning environment, survey and semi structured interviews, we wish to collate understanding to understand strategies of content representation in VR learning environments.

Right: By no means should you feel forced to participate in this interview. You can withdraw your consent and stop your participation in the interview now, or at any time, without affecting your relationship with IIIT Delhi and without loss of any benefits to which you may otherwise be entitled. If you are under 18, you cannot be interviewed.

Confidentiality: I understand that the interviews, transcripts, audio files, video files and study results will be treated as follows to maintain confidentiality:
- Each interviewee will be assigned a random number.
- Only authorized members of the research group will have access to the audio files, video files and transcripts. Audio and video files will be kept in a password-protected computer by researchers affiliated with Prof Pushpendra Singh.

I understand that by giving my consent, I give Ms. Manshul V Belani and her fellow researchers permission to present this work in written and/or other forms for teaching or presentations to advance the knowledge of science and/or academia, without further permission from me.

Contact information. If you have any questions about this study, you should feel free to ask them before the interview, or anytime throughout the interview or by contacting:
Ms. Manshul V. Belani, Department, IIIT, Delhi, 110020,
manshulb@iiitd.ac.in (email).

For any questions pertaining to your rights as a research participant, our objections to the study, you may contact IRB Chair, Designing Human Centered Systems Administration, Indraprastha Institute of Information Technology, Email: ratan.suri@iiitd.ac.in

* Indicates required question

1. *

Do you consent to participate in the study?

Mark only one oval.

- Yes
- No

Demographics

2. Participant ID (please refer to the study modulator) *

3. Instructional Placement Module ((please refer to the study modulator) * Dropdc

Mark only one oval.

- TV Screen
- Controllers
- HMD
- Object

4. *

What is your age?

Mark only one oval.

- ◯ Under 18
- ◯ 18-24
- ◯ 25-34
- ◯ 35-44
- ◯ 45-54
- ◯ 55-64
- ◯ 65+

5. *

What is your gender?

Mark only one oval.

- ◯ Female
- ◯ Male
- ◯ Other: _____

6. *

At what email address would you like to be contacted?

_____

7. Contact No.

_____

8. Please indicate how familiar would you consider yourself to be with the topic of laser cutting.

Mark only one oval.

- Extremely familiar
- Very familiar
- Somewhat familiar
- Not so familiar
- Not at all familiar

9. Please indicate your experience with using VR applications? *

Mark only one oval.

- Extremely experienced (expert)
- Very experienced
- Somewhat experienced
- Not so experienced
- Not at all experienced

Knowledge Gain

10. LASER stands for

Mark only one oval.

- Light amplification by stimulated emission of radiation
- Light amplification by stimulated erosion of reaction
- Light amplification by stimulated erosion of radiation
- Light amplification by stimulated emission of reaction

11. In laser beam machining process, lens is used to

Mark only one oval.

- Deflect laser beams
- Diverge laser beams
- Converge laser beams
- None of the above

12. What is the type of laser did you learn to operate in the tutorial (also the most widely used industrial materials processing applications)?

Mark only one oval.

- Dye laser
- YAG laser
- Ruby laser
- Carbon dioxide laser

13. In which task does the laser cutting machine changes only the color of the material but does not remove material?

Mark only one oval.

- Cutting
- Engraving
- Marking
- None of the above

14. What should be the distance between the material placed in the machine and the tip of the laser nozzle?

Mark only one oval.

- 7mm
- 10mm
- 15mm
- 5mm

15. Which buttons are used to set the placement of nozzle on the material where laser cutting has to be performed?

Mark only one oval.

- Z/U, Origin and Arrows
- Z/U, Frame and Arrows
- Arrows, Origin and Frame
- All of the above

16. For laser cutters to work, a laser beam is directed onto the material with a precise

Mark only one oval.

- focal length
- power
- distance
- intensity

17. What kind of input file can be provided to a laser cutting machine to be cut, etched or engraved?

Mark only one oval.

- Only raster images
- Only vector images
- Either of the above
- None of the above

18. What controls the number of laser pulses are applied to the piece you're cutting, every inch?

Mark only one oval.

- Power
- Frequency
- Speed
- None of the above

19. Which materials can be used to cut/etch/engrave using the laser cutting machine?

Mark only one oval.

- Acrylic
- Wood
- Glass
- Brass
- None of the above
- All of the above

Experience WL 1

20. In the lecture that just finished I invested *

Mark only one oval.

- very, very low mental effort
- very low mental effort
- low mental effort
- rather low mental effort
- neither low nor high mental effort
- rather high mental effort
- high mental effort
- very high mental effort
- very, very high mental effort

21. The lecture that just finished was *

Mark only one oval.

- very, very easy
- very easy
- easy
- rather easy
- neither easy nor difficult
- rather difficult
- difficult
- very difficult
- very very difficult

22. To learn from the lecture was *

Mark only one oval.

- very, very easy
- very easy
- easy
- rather easy
- neither easy nor difficult
- rather difficult
- difficult
- very difficult
- very very difficult

23. How much did you concentrate during the lecture? *

Mark only one oval.

- very, very little
- very little
- little
- rather little
- neither little nor much
- rather much
- much
- very much
- very very much

Experience WL 2

Please respond to each of the questions on the following scale (0 meaning not at all the case and 10 meaning completely the case)

24. The topic/topics covered in the activity was/were very complex. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

25. The activity covered formulas that I perceived as very complex. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

26. The activity covered concepts and definitions that I perceived as very complex. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

27. The instructions and/or explanations during the activity were very unclear. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

28. The instructions and/or explanations were full of unclear language. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

29. The instructions and/or explanations were, in terms of learning, very ineffective. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

30. The activity really enhanced my understanding of the topic(s) covered. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

31. The activity really enhanced my knowledge and understanding of statistics. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

32. The activity really enhanced my understanding of the formulas covered. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

33. The activity really enhanced my understanding of concepts and definitions. *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9	10
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

User Experience

Please assess the system by ticking one circle per line.

34. *

Mark only one oval.

	1	2	3	4	5	6	7	
Ann	◯	◯	◯	◯	◯	◯	◯	Enjoyable

35. *

Mark only one oval.

	1	2	3	4	5	6	7	
not	◯	◯	◯	◯	◯	◯	◯	understandable

36. *

Mark only one oval.

	1	2	3	4	5	6	7	
crea	◯	◯	◯	◯	◯	◯	◯	dull

37. *

Mark only one oval.

	1	2	3	4	5	6	7	
easy	◯	◯	◯	◯	◯	◯	◯	difficult to learn

38. *

Mark only one oval.

	1	2	3	4	5	6	7	
valu	◯	◯	◯	◯	◯	◯	◯	inferior

39. *

Mark only one oval.

	1	2	3	4	5	6	7	
bori	◯	◯	◯	◯	◯	◯	◯	exciting

40. *

Mark only one oval.

	1	2	3	4	5	6	7	
not i	◯	◯	◯	◯	◯	◯	◯	interesting

41. *

Mark only one oval.

	1	2	3	4	5	6	7	
unpı	◯	◯	◯	◯	◯	◯	◯	predictable

42. *

Mark only one oval.

	1	2	3	4	5	6	7	
fast	◯	◯	◯	◯	◯	◯	◯	slow

43. *

Mark only one oval.

	1	2	3	4	5	6	7	
inve	◯	◯	◯	◯	◯	◯	◯	conventional

44. *

Mark only one oval.

	1	2	3	4	5	6	7	
obst	◯	◯	◯	◯	◯	◯	◯	supportive

45. *

Mark only one oval.

	1	2	3	4	5	6	7	
goo	◯	◯	◯	◯	◯	◯	◯	bad

46. *

Mark only one oval.

	1	2	3	4	5	6	7	
com	◯	◯	◯	◯	◯	◯	◯	easy

47. *

Mark only one oval.

	1	2	3	4	5	6	7	
unlil	◯	◯	◯	◯	◯	◯	◯	pleasing

48. *

Mark only one oval.

	1	2	3	4	5	6	7	
usua	◯	◯	◯	◯	◯	◯	◯	leading edge

49. *

Mark only one oval.

	1	2	3	4	5	6	7	
unpl	◯	◯	◯	◯	◯	◯	◯	pleasant

50. *

Mark only one oval.

	1	2	3	4	5	6	7	
secu	◯	◯	◯	◯	◯	◯	◯	not secure

51. *

Mark only one oval.

	1	2	3	4	5	6	7	
mot	◯	◯	◯	◯	◯	◯	◯	demotivating

52. *

Mark only one oval.

	1	2	3	4	5	6	7	
mee	◯	◯	◯	◯	◯	◯	◯	does not meet expectations

53. *

Mark only one oval.

	1	2	3	4	5	6	7	
inef	◯	◯	◯	◯	◯	◯	◯	effecient

54. *

Mark only one oval.

	1	2	3	4	5	6	7	
clea	◯	◯	◯	◯	◯	◯	◯	confusing

55. *

Mark only one oval.

	1	2	3	4	5	6	7	
impı	◯	◯	◯	◯	◯	◯	◯	practical

56. *

Mark only one oval.

	1	2	3	4	5	6	7	
orgɑ	◯	◯	◯	◯	◯	◯	◯	cluttered

57. *

Mark only one oval.

	1	2	3	4	5	6	7	
attrɑ	◯	◯	◯	◯	◯	◯	◯	unattractive

58. *

Mark only one oval.

	1	2	3	4	5	6	7	
frier	◯	◯	◯	◯	◯	◯	◯	unfriendly

59. *

Mark only one oval.

	1	2	3	4	5	6	7	
cons	◯	◯	◯	◯	◯	◯	◯	innovative

Please fill the NASA TLX (on the iPad - please refer to the study modulator)

Thank you!!

Thank you for taking out time for this study and giving your feedback. Your feedback is really valuable to us and will help is in creating more optimum VR learning environments.

60. Would you be willing to participate in a follow up study in the coming weeks? *

Mark only one oval.

- ◯ Yes
- ◯ No

61. Any other comments/feedback.

Follow Up Study - Spatial Representation of Learning Content in VR

Consent Form

Principal Investigator: Prof Pushpendra Singh
Affiliated Interviewers: Ms. Manshul Belani

Neither IIIT Delhi, nor these researchers will receive any financial benefit based on the study results. This study has been approved by IIIT Delhi's Institutional Review Board (IRB).

Purpose of the study: The researchers want to evaluate the effects of different spatial representations of learning content in VR education environments.

Interview procedure: You will be asked about your overall experience with the system.

Risks / discomforts / costs: The experience is expected to be inherently interesting and a generally positive experience. There will be no (other) cost to participating other than your time.

Research benefits: The specific objective of the study is to understand the effect of various placements of learning content in VR learning environments on learning metrics. Through a prototype learning environment, survey and semi structured interviews, we wish to collate understanding to understand strategies of content representation in VR learning environments.

Right: By no means should you feel forced to participate in this interview. You can withdraw your consent and stop your participation in the interview now, or at any time, without affecting your relationship with IIIT Delhi and without loss of any benefits to which you may otherwise be entitled. If you are under 18, you cannot be interviewed.

Confidentiality: I understand that the interviews, transcripts, audio files, video files and study results will be treated as follows to maintain confidentiality:
- Each interviewee will be assigned a random number.
- Only authorized members of the research group will have access to the audio files, video files and transcripts. Audio and video files will be kept in a password-protected computer by researchers affiliated with Prof Pushpendra Singh.

I understand that by giving my consent, I give Ms. Manshul V Belani and her fellow researchers permission to present this work in written and/or other forms for teaching or presentations to advance the knowledge of science and/or academia, without further permission from me.

Contact information. If you have any questions about this study, you should feel free to ask them before the interview, or anytime throughout the interview or by contacting:
Ms. Manshul V. Belani, Department, IIIT, Delhi, 110020,
manshulb@iiitd.ac.in (email).

For any questions pertaining to your rights as a research participant, our objections to the study, you may contact IRB Chair, Designing Human Centered Systems Administration, Indraprastha Institute of Information Technology, Email: ratan.suri@iiitd.ac.in

* Indicates required question

1. *

Do you consent to participate in the study?

Mark only one oval.

- Yes
- No

Demographics

2. Participant ID (please refer to the study modulator) *

3. *

What is your age?

Mark only one oval.

- Under 18
- 18-24
- 25-34
- 35-44
- 45-54
- 55-64
- 65+

4. *

What is your gender?

Mark only one oval.

- ◯ Female
- ◯ Male
- ◯ Other: _____

5. *

At what email address would you like to be contacted?

_____

6. Contact No.

_____

7. Please indicate how familiar would you consider yourself to be with the topic of laser cutting.

Mark only one oval.

- ◯ Extremely familiar
- ◯ Very familiar
- ◯ Somewhat familiar
- ◯ Not so familiar
- ◯ Not at all familiar

8. Please indicate your experience with using VR applications? *

Mark only one oval.

- ◯ Extremely experienced (expert)
- ◯ Very experienced
- ◯ Somewhat experienced
- ◯ Not so experienced
- ◯ Not at all experienced

Knowledge Gain

9. LASER stands for

Mark only one oval.

- ◯ Light amplification by stimulated emission of radiation
- ◯ Light amplification by stimulated erosion of reaction
- ◯ Light amplification by stimulated erosion of radiation
- ◯ Light amplification by stimulated emission of reaction

10. In laser beam machining process, lens is used to

Mark only one oval.

- ◯ Deflect laser beams
- ◯ Diverge laser beams
- ◯ Converge laser beams
- ◯ None of the above

11. What is the type of laser did you learn to operate in the tutorial (also the most widely used industrial materials processing applications)?

Mark only one oval.

- Dye laser
- YAG laser
- Ruby laser
- Carbon dioxide laser

12. In which task does the laser cutting machine changes only the color of the material but does not remove material?

Mark only one oval.

- Cutting
- Engraving
- Marking
- None of the above

13. What should be the distance between the material placed in the machine and the tip of the laser nozzle?

Mark only one oval.

- 7mm
- 10mm
- 15mm
- 5mm

14. Which buttons are used to set the placement of nozzle on the material where laser cutting has to be performed?

Mark only one oval.

- ◯ Z/U, Origin and Arrows
- ◯ Z/U, Frame and Arrows
- ◯ Arrows, Origin and Frame
- ◯ All of the above

15. For laser cutters to work, a laser beam is directed onto the material with a precise

Mark only one oval.

- ◯ focal length
- ◯ power
- ◯ distance
- ◯ intensity

16. What kind of input file can be provided to a laser cutting machine to be cut, etched or engraved?

Mark only one oval.

- ◯ Only raster images
- ◯ Only vector images
- ◯ Either of the above
- ◯ None of the above

17. What controls the number of laser pulses are applied to the piece you're cutting, every inch?

Mark only one oval.

- ◯ Power
- ◯ Frequency
- ◯ Speed
- ◯ None of the above

18. Which materials can be used to cut/etch/engrave using the laser cutting machine?

Mark only one oval.

- ◯ Acrylic
- ◯ Wood
- ◯ Glass
- ◯ Brass
- ◯ None of the above
- ◯ All of the above

Pre-questionnaire: Redundancy Principle for Learning Content in VR

CONSENT FORM
Project Title: Comparative Analysis of Design Parameters in Virtual Reality Learning Environments (VRLEs)

Sponsor: NA

Principal Investigator: Dr Pushpendra Singh
Affiliated Researchers: Manshul Belani

Financial Benefits: Neither the Research Funding Division, Indraprastha Institute of Information Technology, nor IIIT-D will receive any financial benefit based on the study results.

Approval: This study has been approved by the Institutional Review Board (IRB), IIIT-D.

Purpose of the Study: To compare and analyse various possible parameters of design dimensions in the context of the representation of learning content in VRLEs and establish the groundwork for a framework to aid in the development of effective, efficient and adaptive VRLEs.

Proposed Research Task: You will be asked to undergo a tutorial in a VR environment followed by a questionnaire and a small interview about your overall experience with the system.

Compensation: The survey is expected to take a maximum of 60 minutes, and you will receive Amazon Vouchers as compensation.

Risks/discomforts/costs: The experience is expected to be a generally positive one. There will be no (other) cost to participating other than your time.

Benefits of Taking Part in the Research Study: Participants will learn using various machines used in industrial labs and gain access to experience virtual reality.

Voluntary Participation: I understand that participation in this study is strictly voluntary. You can withdraw your consent and stop your participation in the interview now, or at any time, without affecting your relationship with IIIT-D and without loss of any benefits to which you may otherwise be entitled. If you are under 18, you cannot take part in this study without the explicit written consent of your parent /guardian.

Confidentiality: I understand that the interviews, transcripts, audio files and study results will be treated as follows to maintain confidentiality: Each interviewee will be assigned a random number. Only authorized members of the research group will have access to the audio files and transcripts. Audio files will be kept in password-protected computers by researchers affiliated with the PI.

Contact information: I understand that by giving my consent, I give Ms. Manshul V Belani and her fellow researchers permission to present this work in written and/or other forms for teaching or presentations to advance the knowledge of science and/or academia, without further permission from me.

Contact information. If you have any questions about this study, you should feel free to ask them before the

interview, or anytime throughout the interview or by contacting:
Ms. Manshul Belani, Department, IIIT, Delhi, 110020,
manshulb@iiitd.ac.in (email)

For any questions pertaining to your rights as a research participant, your objections to the study, you may contact: IRB Chair, Indraprastha Institute of Information Technology, Delhi |Email: IRB@IIITD.AC.IN

* Indicates required question

1. Do you consent to participate in the study?

   Mark only one oval.

   - ◯ Yes
   - ◯ No

Demographics

2. Participant ID (please refer to the study modulator) *

   _____

3. Iteration ID (please check with the study coordinator) *

   _____

4. Age *

   _____

5. Gender *

   Mark only one oval.

   - ◯ Male
   - ◯ Female
   - ◯ Prefer not to say

6. Email *

7. Contact No. *

8. Institute *

9. Please indicate your experience with using VR applications? *

Mark only one oval.

- Extremely experienced (expert- use VR on a regular basis)
- Very experienced (have used VR multiple times but not a regular user/recently)
- Somewhat experienced (have used VR 3-5 times)
- Not so experienced (have used VR once or twice)
- Not at all experienced (have never used VR)

10. Please indicate how familiar would you consider yourself to be with a 3D printer? *

Mark only one oval.

- Extremely familiar (use the 3D printer on a regular basis)
- Very familiar (have used 3D printer multiple times but not on a regular basis/recently)
- Somewhat familiar (have used a 3D printer 3-5 times)
- Not so familiar (have used 3D printer once or twice)
- Not at all familiar (have never used 3D printer)

11. Please indicate how familiar would you consider yourself to be with the topic/concept of 3D printing.

Mark only one oval.

- Extremely familiar
- Very familiar
- Somewhat familiar
- Not so familiar
- Not at all familiar

Knowledge Gain

12. Which form of manufacturing involves the removal of material from the workpiece to obtain the desired shape? *

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

13. Which form of manufacturing involves obtaining the product by pouring material into a mould of the desired shape and allowing its solidification?

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

14. 3D printing forms an example of which type of manufacturing? *

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

15. Stamping is an example of which form of manufacturing? *

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

16. Which of the following materials cannot be used by a 3D printer to create things? *

Mark only one oval.

- Plastic
- Clothes
- Metals
- Biological materials
- I do not know

17. Which of the following preprocessing steps need to be performed before printing a 3D model? *

Mark only one oval.

- Mirroring
- Rotating
- Scaling
- Slicing
- I do not know

18. Which setting determines the density of the 3D model to be printed? *

Mark only one oval.

- Resolution
- Infill density
- Adhesion
- Support
- I do not know

19. Which setting affects the finishing of the 3D model to be printed? *

Mark only one oval.

- Resolution
- Infill density
- Adhesion
- Support
- I do not know

20. What is the purpose of slicing? *

Mark only one oval.

- slices are vertical cross sections of the 3D model which are sequentially stacked side by side to fori the final product
- slices are horizontal cross-sections of the model which are sequentially stacked above one another to form the final product
- Both (a) and (b) can happen
- None of the above
- I do not know

Post-questionnaire: Redundancy Principle for Learning Content in VR

* Indicates required question

Demographics

1. Participant ID

_____

Knowledge Gain

2. Which form of manufacturing involves reshaping the material without any removal of it? *

Mark only one oval.

- ◯ Subtractive
- ◯ Forming
- ◯ Casting
- ◯ Additive
- ◯ I do not know

3. Which form of manufacturing do techniques like milling and drilling classify into? *

Mark only one oval.

- ◯ Subtractive
- ◯ Forming
- ◯ Casting
- ◯ Additive
- ◯ I do not know

4. Which form of manufacturing involves obtaining the desired product by deposition of the material layer by layer? *

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

5. Which of these is not a type of 3D printing technology?

Mark only one oval.

- SLA
- FDM
- FDA
- SLS
- I do not know

6. Which of these would you aim for to improve the finish of the 3D model? *

Mark only one oval.

- Lower layer height
- Higher layer height
- Higher infill density
- Lower infill density
- I do not know

7. At what angle should the material to be inserted in the 3D printer be cut at the tip to help smooth feeding into the printer?

Mark only one oval.

- 90
- 60
- 45
- 30
- I do not know

8. What is meant by the term “Slicing” in the 3D printing process? *

Mark only one oval.

- ◯ Slicing the 3D digital model into thin vertical layers
- ◯ Slicing the 3D digital model into thin horizontal layers
- ◯ Slicing the 3D digital model into quadrant segments
- ◯ Either (1) or (2).
- ◯ I do not know

9. What is the standard infill density range for 3D printing?

Mark only one oval.

- ◯ 10% - 30%
- ◯ 70%-100%
- ◯ 15% - 50%
- ◯ 55% - 90%
- ◯ I do not know

10. What is the use of support structures in the process of 3D printing? *

Mark only one oval.

- ◯ ensure stability
- ◯ provide scaffolding to hold up overhanging parts
- ◯ prevent deformations
- ◯ All of the above
- ◯ I do not know

11. Which form of manufacturing involves the removal of material from the workpiece to obtain the desired shape? *

Mark only one oval.

- ◯ Subtractive
- ◯ Forming
- ◯ Casting
- ◯ Additive
- ◯ I do not know

12. Which form of manufacturing involves obtaining the product by pouring material into a mould of the desired shape and allowing its solidification?

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

13. Stamping is an example of which form of manufacturing? *

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

14. Which of the following materials cannot be used by a 3D printer to create things? *

Mark only one oval.

- Plastic
- Clothes
- Metals
- Biological materials
- I do not know

15. Which setting determines the density of the 3D model to be printed? *

Mark only one oval.

- Resolution
- Infill density
- Adhesion
- Support
- I do not know

16. Which setting affects the finishing of the 3D model to be printed? *

Mark only one oval.

- Resolution
- Infill density
- Adhesion
- Support
- I do not know

17. Which of the following preprocessing steps need to be performed before printing a 3D model? *

Mark only one oval.

- Mirroring
- Rotating
- Scaling
- Slicing
- I do not know

18. What is the purpose of slicing? *

Mark only one oval.

- slices are vertical cross sections of the 3D model which are sequentially stacked side by side to form the final product
- slices are horizontal cross-sections of the model which are sequentially stacked above one another to form the final product
- Both (a) and (b) can happen
- None of the above
- I do not know

19. 3D printing forms an example of which type of manufacturing? *

Mark only one oval.

- Subtractive
- Forming
- Casting
- Additive
- I do not know

REFERENCES

[1] S. F. Alfalah, "Perceptions toward adopting virtual reality as a teaching aid in information technology," *Education and Information Technologies*, vol. 23, no. 6, pp. 2633–2653, 2018.

[2] H. Ardiny and E. Khanmirza, "The role of ar and vr technologies in education developments: Opportunities and challenges," in *2018 6th rsi international conference on robotics and mechatronics (icrom)*, IEEE, 2018, pp. 482–487.

[3] D. Hamilton, J. McKechnie, E. Edgerton, and C. Wilson, "Implementing immersive virtual reality in higher education: A qualitative study of instructor attitudes and perspectives," *Innovative Practice in Higher Education*, vol. 4, no. 2, 2021.

[4] R. Lege and E. Bonner, "Virtual reality in education: The promise, progress, and challenge," *The Jalt Call Journal*, vol. 16, no. 3, pp. 167–180, 2020.

[5] L. Jensen and F. Konradsen, "A review of the use of virtual reality head-mounted displays in education and training," *Education and Information Technologies*, vol. 23, pp. 1515–1529, 2018.

[6] D. Hamilton, J. McKechnie, E. Edgerton, and C. Wilson, "Immersive virtual reality as a pedagogical tool in education: A systematic literature review of quantitative learning outcomes and experimental design," *Journal of Computers in Education*, vol. 8, no. 1, pp. 1–32, 2021.

[7] S. Kavanagh, A. Luxton-Reilly, B. Wuensche, and B. Plimmer, "A systematic review of virtual reality in education," *Themes in science and technology education*, vol. 10, no. 2, pp. 85–119, 2017.

[8] V. S. Pantelidis, "Reasons to use virtual reality in education and training courses and a model to determine when to use virtual reality," *Themes in Science and Technology Education*, vol. 2, no. 1-2, pp. 59–70, 2010.

[9] M. Cook et al., "Challenges and strategies for educational virtual reality: Results of an expert-led forum on 3d/vr technologies across academic institutions," *Information Technology and Libraries*, vol. 38, no. 4, pp. 25–48, 2019.

[10] E. C. Hamilton et al., "Comparison of video trainer and virtual reality training systems on acquisition of laparoscopic skills," *Surgical Endoscopy and Other Interventional Techniques*, vol. 16, no. 3, pp. 406–411, 2002.

[11] C. Loukas, N. Nikiteas, D. Schizas, V. Lahanas, and E. Georgiou, "A head-to-head comparison between virtual reality and physical reality simulation training for basic skills acquisition," *Surgical endoscopy*, vol. 26, no. 9, pp. 2550–2558, 2012.

[12] I. Yavrucuk, E. Kubali, and O. Tarimci, "A low cost flight simulator using virtual reality tools," *IEEE Aerospace and Electronic Systems Magazine*, vol. 26, no. 4, pp. 10–14, 2011.

[13] G. Makransky, T. S. Terkildsen, and R. E. Mayer, "Adding immersive virtual reality to a science lab simulation causes more presence but less learning," *Learning and Instruction*, vol. 60, pp. 225–236, 2019.

[14] R. E. Mayer and R. Moreno, "A cognitive theory of multimedia learning: Implications for design principles," *Journal of educational psychology*, vol. 91, no. 2, pp. 358–368, 1998.

[15] C. Lankshear and M. Knobel, *New literacies: Changing knowledge and classroom learning*. Open University Press, 2003.

[16] S. Baceviciute, T. Terkildsen, and G. Makransky, "Remediating learning from non-immersive to immersive media: Using eeg to investigate the effects of environmental embeddedness on reading in virtual reality," *Computers & Education*, vol. 164, p. 104 122, 2021.

[17] S. Baceviciute, "Designing virtual reality for learning," Ph.D. dissertation, University of Copenhagen, 2020.

[18] E. Z. Borba, M. Cabral, A. Montes, O. Belloc, and M. Zuffo, "Immersive and interactive procedure training simulator for high risk power line maintenance," in *ACM SIGGRAPH 2016 VR Village*, 2016, pp. 1–1.

[19] Y. Hernández and M. P. Ramírez, "Virtual reality systems for training improvement in electrical distribution substations," in *2016 IEEE 16th International Conference on Advanced Learning Technologies (ICALT)*, IEEE, 2016, pp. 75–76.

[20] E. H. Tanaka et al., "Immersive virtual training for substation electricians," in *2017 IEEE Virtual Reality (VR)*, IEEE, 2017, pp. 451–452.

[21] J. Bertram, J. Moskaliuk, and U. Cress, "Virtual training: Making reality work?" *Computers in Human Behavior*, vol. 43, pp. 284–292, 2015.

[22] F. Crison, A. Lecuyer, D. M. d'Huart, J.-M. Burkhardt, G. Michel, and J.-L. Dautin, "Virtual technical trainer: Learning how to use milling machines with multi-sensory feedback in virtual reality," in *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, IEEE, 2005, pp. 139–145.

[23] E. Blümel and T. Haase, "Virtual reality platforms for education and training in industry," in *East European Conference on Advances in Databases and Information Systems*, Springer, 2009, pp. 1–7.

[24] J. Siemon, L. M. Muñoz, and M. I. Berasategi, "Virtool–a vr-based learning environment for the vocational training in machine-tool processes," in *The 6th World Multiconference on Systemics, Cybernetics and Informatics Proceedings-Concepts and Applications of Systemics, Cybernetics and Informatics*, Citeseer, vol. 2, 2002, pp. 267–270.

[25] M. Belani, "Evaluating virtual reality as a medium for vocational skill training," in *Extended abstracts of the 2020 CHI conference on human factors in computing systems*, 2020, pp. 1–8.

[26] B. Lu, K. Lim, J. Zheng, and Y. Cai, "Learning molecular biology by vr playing," in *Proceedings of the 2004 ACM SIGGRAPH international conference on Virtual Reality continuum and its applications in industry*, 2004, pp. 168–172.

[27] J. H. Seo et al., "Anatomy builder vr: Applying a constructive learning method in the virtual reality canine skeletal system," in *International Conference on Applied Human Factors and Ergonomics*, Springer, 2017, pp. 245–252.

[28] E. Ye16, Y. Fang, C. Liu18, T. J. Chang19, and H. Q. Dinh, "Appalachian tycoon: An environmental education game in second life," in *Second life education workshop 2007*, Citeseer, 2007, p. 72.

[29] J. Detlefsen, "The cosmic perspective: Teaching middle-school children astronomy using ego-centric virtual reality," *Unpublished master's thesis). Aalborg University, Medialogy, Aalborg*, 2014.

[30] J. Pirker, A. Dengel, M. Holly, and S. Safikhani, "Virtual reality in computer science education: A systematic review," in *26th ACM symposium on virtual reality software and technology*, 2020, pp. 1–8.

[31] M. Patera, M. Naef, and S. Draper, "The magic cottage: A virtual reality environment for stimulating children's imaginative writing,"

[32] T. G. Moesgaard, J. Fiss, C. Warming, J. Klubien, and H. Schoenau-Fog, "Implicit and explicit information mediation in a virtual reality museum installation and its effects on retention and learning outcomes," in *Proceedings of the 9th European Conference on Games-Based Learning: ECGBL 2015*, Academic Conferences and Publishing International, 2015, pp. 387–394.

[33] J. W. Woodworth, S. Ekong, and C. W. Borst, "Virtual field trips with networked depth-camera-based teacher, heterogeneous displays, and example energy center application," in *2017 IEEE Virtual Reality (VR)*, IEEE, 2017, pp. 471–472.

[34] A. Cheng, L. Yang, and E. Andersen, "Teaching language and culture with a virtual reality game," in *Proceedings of the 2017 CHI conference on human factors in computing systems*, 2017, pp. 541–549.

[35] S. Garcia, R. Kauer, D. Laesker, J. Nguyen, and M. Andujar, "A virtual reality experience for learning languages," in *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–4.

[36] K. R. Butcher, "The multimedia principle," *The Cambridge handbook of multimedia learning*, vol. 2, pp. 174–205, 2014.

[37] R. E. Mayer and L. Fiorella, "12 principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles," *The Cambridge handbook of multimedia learning*, vol. 279, 2014.

[38] P. Ayres and J. Sweller, "The split-attention principle in multimedia learning," *The Cambridge handbook of multimedia learning*, vol. 2, pp. 135–146, 2005.

[39] T. Van Gog, "11–the signaling (or cueing) principle in multimedia learning," *The Cambridge handbook of multimedia learning*, pp. 263–278, 2014.

[40] H. K. Tabbers, R. L. Martens, and J. J. Van Merrienboer, "The modality effect in multimedia instructions," in *Proceedings of the Annual Meeting of the Cognitive Science Society*, vol. 23, 2001.

[41] D. Y. Lee and D.-H. Shin, "An empirical evaluation of multi-media based learning of a procedural task," *Computers in Human Behavior*, vol. 28, no. 3, pp. 1072–1081, 2012.

[42] R. Moreno, "Does the modality principle hold for different media? a test of the method-affects-learning hypothesis," *Journal of Computer Assisted Learning*, vol. 22, no. 3, pp. 149–158, 2006.

[43] G. Watson, J. Butterfield, R. Curran, and C. Craig, "Do dynamic work instructions provide an advantage over static instructions in a small scale assembly task?" *Learning and Instruction*, vol. 20, no. 1, pp. 84–93, 2010.

[44] C. van Hooijdonk and E. Krahmer, "Information modalities for procedural instructions: The influence of text, pictures, and film clips on learning and executing rsi ex-

ercises," *IEEE Transactions on Professional Communication*, vol. 51, no. 1, pp. 50–62, 2008.

[45] L. Liberman and I. Dubovi, "The effect of the modality principle to support learning with virtual reality: An eye-tracking and electrodermal activity study," *Journal of Computer Assisted Learning*, vol. 39, no. 2, pp. 547–557, 2023.

[46] R. Moreno and R. E. Mayer, "Learning science in virtual reality multimedia environments: Role of methods and media.," *Journal of educational psychology*, vol. 94, no. 3, p. 598, 2002.

[47] R. Moreno and R. E. Mayer, "Verbal redundancy in multimedia learning: When reading helps listening.," *Journal of educational psychology*, vol. 94, no. 1, p. 156, 2002.

[48] R. E. Mayer, J. Heiser, and S. Lonn, "Cognitive constraints on multimedia learning: When presenting more material results in less understanding.," *Journal of educational psychology*, vol. 93, no. 1, p. 187, 2001.

[49] S. Baceviciute, A. Mottelson, T. Terkildsen, and G. Makransky, "Investigating representation of text and audio in educational vr using learning outcomes and eeg," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–13.

[50] S. Baceviciute, G. Lucas, T. Terkildsen, and G. Makransky, "Investigating the redundancy principle in immersive virtual reality environments: An eye-tracking and eeg study," *Journal of Computer Assisted Learning*, vol. 38, no. 1, pp. 120–136, 2022.

[51] T. Dingler, K. Kunze, and B. Outram, "Vr reading uis: Assessing text parameters for reading in vr," in *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, 2018, pp. 1–6.

[52] C. W. Borst, N. G. Lipari, and J. W. Woodworth, "Teacher-guided educational vr: Assessment of live and prerecorded teachers guiding virtual field trips," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, 2018, pp. 467–474.

[53] A. L. Simeone, M. Speicher, A. Molnar, A. Wilde, and F. Daiber, "Live: The human role in learning in immersive virtual environments," in *Symposium on Spatial User Interaction*, 2019, pp. 1–11.

[54] G. B. Petersen, A. Mottelson, and G. Makransky, "Pedagogical agents in educational vr: An in the wild study," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–12.

[55] R. Rzayev, S. Mayer, C. Krauter, and N. Henze, "Notification in vr: The effect of notification placement, task and environment," in *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, 2019, pp. 199–211.

[56] C.-Y. Hsieh, Y.-S. Chiang, H.-Y. Chiu, and Y.-J. Chang, "Bridging the virtual and real worlds: A preliminary study of messaging notifications in virtual reality," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–14.

[57] S. H. Chua, S. T. Perrault, D. J. Matthies, and S. Zhao, "Positioning glass: Investigating display positions of monocular optical see-through head-mounted display," in *Proceedings of the Fourth International Symposium on Chinese CHI*, 2016, pp. 1–6.

[58] S. Rothe, K. Tran, and H. Hußmann, "Dynamic subtitles in cinematic virtual reality," in *Proceedings of the 2018 ACM International Conference on Interactive Experiences for TV and Online Video*, 2018, pp. 209–214.

[59] R. Rzayev, P. W. Woźniak, T. Dingler, and N. Henze, "Reading on smart glasses: The effect of text position, presentation type and walking," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 2018, pp. 1–9.

[60] F. Mathis, X. Zhang, M. McGill, A. L. Simeone, and M. Khamis, "Assessing social text placement in mixed reality tv," in *ACM International Conference on Interactive Media Experiences*, 2020, pp. 205–211.

[61] A. McNamara, K. Boyd, J. George, W. Jones, S. Oh, and A. Suther, "Information placement in virtual reality," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, 2019, pp. 1765–1769.

[62] J. Dominic and A. Robb, "Exploring effects of screen-fixed and world-fixed annotation on navigation in virtual reality," in *2020 IEEE conference on virtual reality and 3d user interfaces (VR)*, IEEE, 2020, pp. 607–615.

[63] G. B. Petersen, G. Petkakis, and G. Makransky, "A study of how immersion and interactivity drive vr learning," *Computers & Education*, vol. 179, p. 104 429, 2022.

[64] N. Wenk, J. Penalver-Andres, K. A. Buetler, T. Nef, R. M. Müri, and L. Marchal-Crespo, "Effect of immersive visualization technologies on cognitive load, motivation, usability, and embodiment," *Virtual Reality*, vol. 27, no. 1, pp. 307–331, 2023.

[65] J. Zhou, K. Yu, F. Chen, Y. Wang, and S. Z. Arshad, "Multimodal behavioral and physiological signals as indicators of cognitive load," in *The Handbook of*

Multimodal-Multisensor Interfaces: Signal Processing, Architectures, and Detection of Emotion and Cognition-Volume 2, 2018, pp. 287–329.

[66] J. L. Plass, R. Moreno, and R. Brünken, "Cognitive load theory," 2010.

[67] R. Brünken, T. Seufert, and F. Paas, "Measuring cognitive load," 2010.

[68] A. MacLean, R. Young, V. Bellotti, and T. Moran, "Design space analysis: Bridging from theory to practice via design rationale," *Proceedings of Esprit*, vol. 91, no. 720-730, p. 2, 1991.

[69] S. K. Card, J. D. Mackinlay, and G. G. Robertson, "The design space of input devices," in *Proceedings of the SIGCHI conference on Human factors in computing systems*, 1990, pp. 117–124.

[70] R. Ballagas, J. Borchers, M. Rohs, and J. G. Sheridan, "The smart phone: A ubiquitous input device," *IEEE pervasive computing*, vol. 5, no. 1, pp. 70–77, 2006.

[71] R. Ballagas, S. Ghosh, and J. Landay, "The design space of 3d printable interactivity," *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 2, no. 2, pp. 1–21, 2018.

[72] T. Hirzle, J. Gugenheimer, F. Geiselhart, A. Bulling, and E. Rukzio, "A design space for gaze interaction on head-mounted displays," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–12.

[73] T. Drey, J. Gugenheimer, J. Karlbauer, M. Milo, and E. Rukzio, "Vrsketchin: Exploring the design space of pen and tablet interaction for 3d sketching in virtual reality," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–14.

[74] J. Arora, K. Mathur, A. Saini, and A. Parnami, "Gehna: Exploring the design space of jewelry as an input modality," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–12.

[75] M. Lee et al., "A design space for intelligent and interactive writing assistants," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–35.

[76] Y. Liu, A. Shah, J. Ackerman, and M. Saha, "Exploring the design space of real-time llm knowledge support systems: A case study of jargon explanations," in *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, 2025, pp. 1–20.

[77] R. Zheng et al., "Sketchnote components, design space dimensions, and strategies for effective visual note taking," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–15.

[78] E. Eriksson, G. E. Baykal, O. Torgersson, and S. Bjork, "The coce design space: Exploring the design space for co-located collaborative games that use multi-display composition," in *Designing Interactive Systems Conference 2021*, 2021, pp. 718–733.

[79] R. K. d. Anjos et al., "Adventures in hologram space: Exploring the design space of eye-to-eye volumetric telepresence," in *Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology*, 2019, pp. 1–5.

[80] J. Mathew, S. Huot, and A. Blum, "A morphological analysis of audio objects and their control methods for 3d audio," 2014.

[81] S. S. Bae, C. Zheng, M. E. West, E. Y.-L. Do, S. Huron, and D. A. Szafir, "Making data tangible: A cross-disciplinary design space for data physicalization," in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 2022, pp. 1–18.

[82] L. Turmo Vidal, H. Zhu, A. Waern, and E. Márquez Segura, "The design space of wearables for sports and fitness practices," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–14.

[83] D. Kim, S. Lee, Y. Jun, Y. Shin, and J. Lee, "Vtuber's atelier: The design space, challenges, and opportunities for vtubing," in *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, 2025, pp. 1–23.

[84] D. Gonçalves, D. Barros, P. Pais, J. Guerreiro, T. Guerreiro, and A. Rodrigues, "The trick is to stay behind?: Defining and exploring the design space of player balancing mechanics," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–16.

[85] B. Lee, M. Cordeil, A. Prouzeau, B. Jenny, and T. Dwyer, "A design space for data visualisation transformations between 2d and 3d in mixed-reality environments," in *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 2022, pp. 1–14.

[86] K. Danyluk, B. Ens, B. Jenny, and W. Willett, "A design space exploration of worlds in miniature," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–15.

[87] H. Zhang et al., "Ieds: Exploring an intelli-embodied design space combining designer, ar, and gai to support industrial conceptual design," in *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, 2025, pp. 1–25.

[88] S. Rajaram, M. Peralta, J. G. Johnson, and M. Nebeling, "Exploring the design space of privacy-driven adaptation techniques for future augmented reality interfaces," in *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, 2025, pp. 1–19.

[89] S. He et al., "Data cubes in hand: A design space of tangible cubes for visualizing 3d spatio-temporal data in mixed reality," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–21.

[90] X. Yu, B. Lee, and M. Sedlmair, "Design space of visual feedforward and corrective feedback in xr-based motion guidance systems," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–15.

[91] T. Langlotz, J. Sutton, and H. Regenbrecht, "A design space for vision augmentations and augmented human perception using digital eyewear," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–16.

[92] J. Liu et al., "Datadancing: An exploration of the design space for visualisation view management for 3d surfaces and spaces," in *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, 2023, pp. 1–17.

[93] D. Lottridge, R. Weber, E.-R. McLean, H. Williams, J. Cook, and H. Bai, "Exploring the design space for immersive embodiment in dance," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, 2022, pp. 93–102.

[94] D. Zielasko, J. Heib, and B. Weyers, "Systematic design space exploration of discrete virtual rotations in vr," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, 2022, pp. 693–702.

[95] H. Chen, A. Dey, M. Billinghurst, and R. W. Lindeman, "Exploring the design space for multi-sensory heart rate feedback in immersive virtual reality," in *Proceedings of the 29th Australian conference on computer-human interaction*, 2017, pp. 108–116.

[96] S. Büttner et al., "The design space of augmented and virtual reality applications for assistive environments in manufacturing: A visual approach," in *Proceedings of the 10th International Conference on PErvasive Technologies Related to Assistive Environments*, 2017, pp. 433–440.

[97] H. Nicolau, A. Rodrigues, A. Santos, T. Guerreiro, K. Montague, and J. Guerreiro, "The design space of nonvisual word completion," in *Proceedings of the 21st International ACM SIGACCESS Conference on Computers and Accessibility*, 2019, pp. 249–261.

[98] N. W. Kim, S. C. Joyner, A. Riegelhuth, and Y. Kim, "Accessible visualization: Design space, opportunities, and challenges," in *Computer Graphics Forum*, Wiley Online Library, vol. 40, 2021, pp. 173–188.

[99] J. Guerreiro, Y. Kim, R. Nogueira, S. Chung, A. Rodrigues, and U. Oh, "The design space of the auditory representation of objects and their behaviours in virtual reality for blind people," *IEEE Transactions on Visualization and Computer Graphics*, 2023.

[100] F. Zwicky, "The morphological approach to discovery, invention, research and construction," in *New methods of thought and procedure*, Springer, 1967, pp. 273–297.

[101] S. K. Card, J. D. Mackinlay, and G. G. Robertson, "A morphological analysis of the design space of input devices," *ACM Transactions on Information Systems (TOIS)*, vol. 9, no. 2, pp. 99–122, 1991.

[102] G. Cooper, H. Park, Z. Nasr, L. P. Thong, and R. Johnson, "Using virtual reality in the classroom: Preservice teachers' perceptions of its use as a teaching and learning tool," *Educational Media International*, vol. 56, no. 1, pp. 1–13, 2019.

[103] Q. Jin, Y. Liu, S. Yarosh, B. Han, and F. Qian, "How will vr enter university classrooms? multi-stakeholders investigation of vr in higher education," in *Proceedings of the 2022 CHI conference on human factors in computing systems*, 2022, pp. 1–17.

[104] P. Hagge, "Student perceptions of semester-long in-class virtual reality: Effectively using "google earth vr" in a higher education classroom," *Journal of Geography in Higher Education*, vol. 45, no. 3, pp. 342–360, 2021.

[105] E. Southgate et al., "Embedding immersive virtual reality in classrooms: Ethical, organisational and educational lessons in bridging research and practice," *International Journal of Child-Computer Interaction*, vol. 19, pp. 19–29, 2019.

[106] V. Mäkelä, C. MacArthur, J. Lee, and D. Harley, "Integrating virtual reality head-mounted displays into higher education classrooms on a large scale," 2025.

[107] E. L. Deci and R. M. Ryan, "The" what" and" why" of goal pursuits: Human needs and the self-determination of behavior," *Psychological inquiry*, vol. 11, no. 4, pp. 227–268, 2000.

[108] E. L. Deci and R. M. Ryan, *Handbook of self-determination research*. University Rochester Press, 2004.

[109] R. M. Ryan and E. L. Deci, *Self-determination theory: Basic psychological needs in motivation, development, and wellness*. Guilford publications, 2017.

[110] J. Yoo, S. Lee, and E. A. Ohu, "A cross-cultural analysis of vr gaming psychological needs and motivations: A self-determination theory approach," *Managing Sport and Leisure*, vol. 29, no. 3, pp. 392–412, 2024.

[111] F. Reer, L.-O. Wehden, R. Janzik, W. Y. Tang, and T. Quandt, "Virtual reality technology and game enjoyment: The contributions of natural mapping and need satisfaction," *Computers in Human Behavior*, vol. 132, p. 107 242, 2022.

[112] X. Li, X. Ren, X. Suzuki, N. Yamaji, K. W. Fung, and Y. Gondo, "Designing a multisensory vr game prototype for older adults-the acceptability and design implications," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–18.

[113] J. Koulouris, Z. Jeffery, J. Best, E. O'neill, and C. Lutteroth, "Me vs. super (wo) man: Effects of customization and identification in a vr exergame," in *Proceedings of the 2020 CHI conference on human factors in computing systems*, 2020, pp. 1–17.

[114] S. R. Xiong, S. S. Ho, W. Tan, B. J. Li, and G. Lisak, "Virtual environment, real impacts: A self-determination perspective on the use of virtual reality for pro-environmental behavior interventions," *Environmental Communication*, vol. 18, no. 5, pp. 628–647, 2024.

[115] D. Alexandrovsky et al., "Playful user-generated treatment: A novel game design approach for vr exposure therapy," in *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, 2020, pp. 32–45.

[116] M. Chen, C.-S. Chai, M. S.-Y. Jong, and G. C.-N. Chao, "Modeling learners' self-concept in chinese descriptive writing based on the affordances of a virtual reality-supported environment," *Education and Information Technologies*, vol. 26, no. 5, pp. 6013–6032, 2021.

[117] R. Cuthbert, S. Turkay, and R. Brown, "The effects of customisation on player experiences and motivation in a virtual reality game," in *Proceedings of the 31st Australian Conference on Human-Computer-Interaction*, 2019, pp. 221–232.

[118] S. Seinfeld, T. Feuchtner, J. Pinzek, and J. Müller, "Impact of information placement and user representations in vr on performance and embodiment," *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–13, 2020.

[119] R. E. Mayer, "Multimedia learning," in *Psychology of learning and motivation*, vol. 41, Elsevier, 2002, pp. 85–139.

[120] S. Ghosh et al., "Notifivr: Exploring interruptions and notifications in virtual reality," *IEEE transactions on visualization and computer graphics*, vol. 24, no. 4, pp. 1447–1456, 2018.

[121] F. G. Paas, "Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive-load approach.," *Journal of educational psychology*, vol. 84, no. 4, p. 429, 1992.

[122] P. Ayres, "Using subjective measures to detect variations of intrinsic cognitive load within problems," *Learning and instruction*, vol. 16, no. 5, pp. 389–400, 2006.

[123] G. Cierniak, K. Scheiter, and P. Gerjets, "Explaining the split-attention effect: Is the reduction of extraneous cognitive load accompanied by an increase in germane cognitive load?" *Computers in Human Behavior*, vol. 25, no. 2, pp. 315–324, 2009.

[124] G. Salomon, "Television is" easy" and print is" tough": The differential investment of mental effort in learning as a function of perceptions and attributions.," *Journal of educational psychology*, vol. 76, no. 4, p. 647, 1984.

[125] J. Leppink, F. Paas, C. P. Van der Vleuten, T. Van Gog, and J. J. Van Merriënboer, "Development of an instrument for measuring different types of cognitive load," *Behavior research methods*, vol. 45, no. 4, pp. 1058–1072, 2013.

[126] "NASA-TLX." https://humansystems.arc.nasa.gov/groups/tlx/, Last accessed 14/10/2022.

[127] "User Experience Questionnaire." https://www.ueq-online.org/, Last accessed 14/10/2022.

[128] "Designing, Running and Analyzing Experiments." https://www.coursera.org/learn/designexperiments, Last accessed 19/12/2022.

[129] K.-Y. Liu, S.-K. Wong, M. Volonte, E. Ebrahimi, and S. V. Babu, "Investigating the effects of leading and following behaviors of virtual humans in collaborative fine motor tasks in virtual reality," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, 2022, pp. 330–339.

[130] T. A. Mikropoulos and A. Natsis, "Educational virtual environments: A ten-year review of empirical research (1999–2009)," *Computers & Education*, vol. 56, no. 3, pp. 769–780, 2011.

[131] R. Low and J. Sweller, "The modality principle in multimedia learning," *The Cambridge handbook of multimedia learning*, vol. 147, p. 158, 2005.

[132] J. Sweller, "The redundancy principle in multimedia learning.," 2005.

[133] J. R. Anderson, *The architecture of cognition*. Psychology Press, 2013.

[134] D. R. Krathwohl, "A revision of bloom's taxonomy: An overview," *Theory into practice*, vol. 41, no. 4, pp. 212–218, 2002.

[135] V. Braun and V. Clarke, "Using thematic analysis in psychology," *Qualitative Research in Psychology*, vol. 3, no. 2, pp. 77–101, 2006. eprint: https://www.tandfonline.com/doi/pdf/10.1191/1478088706qp063oa.

[136] R. Moreno and R. E. Mayer, "Cognitive principles of multimedia learning: The role of modality and contiguity.," *Journal of educational psychology*, vol. 91, no. 2, p. 358, 1999.

[137] A. Skulmowski and K. M. Xu, "Understanding cognitive load in digital and online learning: A new perspective on extraneous cognitive load," *Educational psychology review*, vol. 34, no. 1, pp. 171–196, 2022.

[138] M. Horne and E. M. Thompson, "The role of virtual reality in built environment education," *Journal for Education in the Built Environment*, vol. 3, no. 1, pp. 5–24, 2008.

[139] J. Joundi, Y. Christiaens, J. Saldien, P. Conradie, and L. De Marez, "An explorative study towards using vr sketching as a tool for ideation and prototyping in product design," in *Proceedings of the Design Society: DESIGN Conference*, Cambridge University Press, vol. 1, 2020, pp. 225–234.

[140] J. Henstrom, R. De Amicis, C. A. Sanchez, and Y. Turkan, "Immersive engineering instruction: Using virtual reality to enhance students' experience in the classroom," *Computers & Graphics*, vol. 121, p. 103 944, 2024.

[141] V. Braun and V. Clarke, *Thematic analysis.* American Psychological Association, 2012.

[142] E. L. Deci and R. M. Ryan, "Self-determination theory," *Handbook of theories of social psychology*, vol. 1, no. 20, pp. 416–436, 2012.

[143] M. Bang, K. Wohn, and C. Shi, "The establishment of an e-learning system based on sdt," *International Journal of Emerging Technologies in Learning (Online)*, vol. 9, no. 4, p. 43, 2014.

[144] T. de Araujo Guerra Grangeia et al., "Cognitive load and self-determination theories applied to e-learning: Impact on students' participation and academic performance," *PloS one*, vol. 11, no. 3, e0152462, 2016.

[145] D. Elford, S. J. Lancaster, and G. A. Jones, "Fostering motivation toward chemistry through augmented reality educational escape activities. a self-determination theory approach," *Journal of chemical education*, vol. 99, no. 10, pp. 3406–3417, 2022.

[146] H. Dhiman, G. A. Rovelo Ruiz, R. Ramakers, D. Leen, and C. Röcker, "Designing instructions using self-determination theory to improve motivation and engagement for learning craft," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–16.

[147] C. J. Gorissen, L. Kester, S. Brand-Gruwel, and R. Martens, "Autonomy supported, learner-controlled or system-controlled learning in hypermedia environments and the influence of academic self-regulation style," *Interactive Learning Environments*, vol. 23, no. 6, pp. 655–669, 2015.

[148] A.-M. Van Loon, A. Ros, and R. Martens, "Motivated learning with digital learning tasks: What about autonomy and structure?" *Educational technology research and development*, vol. 60, pp. 1015–1032, 2012.

[149] N. B. Mendoza, Z. Yan, and R. B. King, "Supporting students' intrinsic motivation for online learning tasks: The effect of need-supportive task instructions on motivation, self-assessment, and task performance," *Computers & Education*, vol. 193, p. 104 663, 2023.

[150] M. Schenkluhn, M. T. Knierim, F. Kiss, and C. Weinhardt, "Connecting home: Human-centric setup automation in the augmented smart home," in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, 2024, pp. 1–16.

[151] I. Miguel-Alonso, B. Rodriguez-Garcia, D. Checa, and A. Bustillo, "Countering the novelty effect: A tutorial for immersive virtual reality learning environments," *Applied Sciences*, vol. 13, no. 1, p. 593, 2023.

[152] S. Moin, M. Belani, P. Singh, N. Phutela, and P. Singh, ""but i won't say that it was bad seeing a real vagina": Understanding perspectives toward learning sensitive-critical health topic," in *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems*, 2025, pp. 1–15.

[153] C. M. Stracke et al., "Immersive virtual reality in higher education: A systematic review of the scientific literature," *Virtual Reality*, vol. 29, no. 2, pp. 1–21, 2025.

[154] C. H.-H. Tsay, A. K. Kofinas, S. K. Trivedi, and Y. Yang, "Overcoming the novelty effect in online gamified learning systems: An empirical evaluation of student engagement and performance," *Journal of Computer Assisted Learning*, vol. 36, no. 2, pp. 128–146, 2020.

[155] X. Wei, X. Jin, G. L. Kan, Y. Yan, and M. Fan, "Systematic literature review of using virtual reality as a social platform in hci community," *arXiv preprint arXiv:2410.11869*, 2024.

[156] D. González-Cutre, Á. Sicilia, A. C. Sierra, R. Ferriz, and M. S. Hagger, "Understanding the need for novelty from the perspective of self-determination theory," *Personality and individual differences*, vol. 102, pp. 159–169, 2016.

[157] P. Brickman, "Hedonic relativism and planning the good society," *Adaptation level theory*, pp. 287–301, 1971.

[158] R. Cors, N. Robin, A. Mueller, and P. Kunz, "Towards a more comprehensive framework for investigating novelty at out-of-school learning places for science and technology learning," *Progress in Science Education (PriSE)*, vol. 1, no. 1, 2018.

[159] C. I. Aguilar Reyes, D. Wozniak, A. Ham, and M. Zahabi, "Design and evaluation of an adaptive virtual reality training system," *Virtual Reality*, vol. 27, no. 3, pp. 2509–2528, 2023.

[160] A. Marougkas, C. Troussas, A. Krouska, and C. Sgouropoulou, "How personalized and effective is immersive virtual reality in education? a systematic literature review for the last decade," *Multimedia Tools and Applications*, vol. 83, no. 6, pp. 18 185–18 233, 2024.

[161] J. Cronje, "Towards a new definition of blended learning," *Electronic journal of e-Learning*, vol. 18, no. 2, pp114–121, 2020.

[162] N. Selwyn, *Education and technology: Key issues and debates*. Bloomsbury Publishing, 2021.

[163] R. P. Norabuena-Figueroa et al., "Digital teaching practices and student academic stress in the era of digitalization in higher education," *Applied Sciences*, vol. 15, no. 3, p. 1487, 2025.

[164] R. Day, "Remediation: Understanding new media," *Journal of the Association for Information Science and Technology*, vol. 50, no. 8, p. 730, 1999.

[165] A. Omazic and B. M. Zunk, "Semi-systematic literature review on sustainability and sustainable development in higher education institutions," *Sustainability*, vol. 13, no. 14, p. 7683, 2021.

[166] E. Eriksson, G. E. Baykal, and O. Torgersson, "The role of learning theory in child-computer interaction-a semi-systematic literature review," in *Proceedings of the 21st Annual ACM Interaction Design and Children Conference*, 2022, pp. 50–68.

[167] G. E. Baykal, E. Eriksson, and O. Torgersson, "Assessment of learning in child–computer interaction research: A semi-systematic literature review," *International Journal of Child-Computer Interaction*, vol. 36, p. 100 578, 2023.

[168] C. Wohlin, "Guidelines for snowballing in systematic literature studies and a replication in software engineering," in *Proceedings of the 18th international conference on evaluation and assessment in software engineering*, 2014, pp. 1–10.

[169] M. Beaudouin-Lafon, "Designing interaction, not interfaces," in *Proceedings of the working conference on Advanced visual interfaces*, 2004, pp. 15–22.

[170] S. Keele et al., *Guidelines for performing systematic literature reviews in software engineering*, 2007.

[171] M. R. Heim, "Virtual reality wave 3," in *Boundaries of self and reality online*, Elsevier, 2017, pp. 261–277.

[172] D. Bowman, E. Kruijff, J. J. LaViola Jr, and I. P. Poupyrev, *3D User interfaces: theory and practice, CourseSmart eTextbook*. Addison-Wesley, 2004.

[173] T. H. Massie, J. K. Salisbury, et al., "The phantom haptic interface: A device for probing virtual objects," in *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, Chicago, IL, vol. 55, 1994, pp. 295–300.

[174] J. Arora, A. Saini, N. Mehra, V. Jain, S. Shrey, and A. Parnami, "Virtualbricks: Exploring a scalable, modular toolkit for enabling physical manipulation in vr," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019, pp. 1–12.

[175] B. S. Bloom et al., "Taxonomy of educational objectives. vol. 1: Cognitive domain," *New York: McKay*, pp. 20–24, 1956.

[176] N. van der Meer, V. van der Werf, W.-P. Brinkman, and M. Specht, "Virtual reality and collaborative learning: A systematic literature review," *Frontiers in Virtual Reality*, vol. 4, p. 1 159 905, 2023.