Investigating Spatial Representation of Learning Content in Virtual Reality Learning Environments

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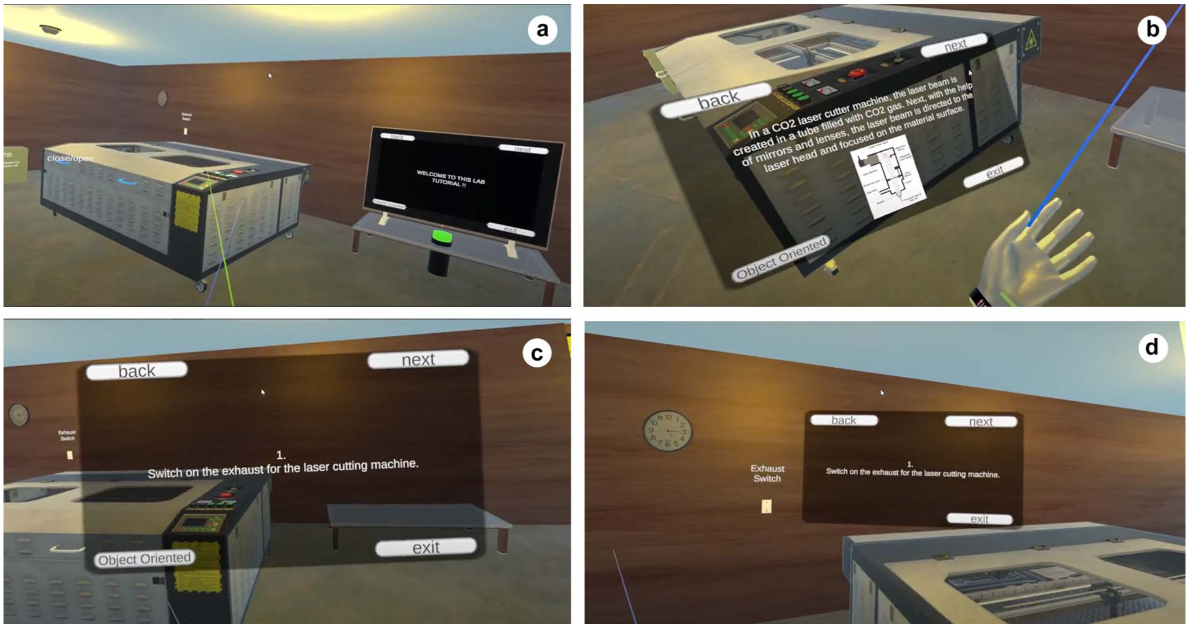

Figure 1: Four Spatial Representations for placement of learning content in VRLEs. (a) World-anchored: on a TV screen fixed in the environment. (b) User-anchored (Controllers): on a panel anchored to the VR controllers. (c) User-anchored (HMD): on a panel anchored to the head-mounted display. (d) Object-anchored: on a panel anchored to the object associated with current instruction.

Abstract

A recent surge in the application of Virtual Reality in education has made VR Learning Environments (VRLEs) prevalent in fields ranging from aviation, medicine, and skill training to teaching factual and conceptual content. In spite of multiple 3D affordances provided by VR, learning content placement in VRLEs has been mostly limited to a static placement in the environment. We conduct two studies to investigate the effect of different spatial representations of learning content in virtual environments on learning outcomes and user experience. In the first study, we studied the effects of placing content at four different places - world-anchored (TV screen placed in the environment), user-anchored (panel anchored to the wrist or head-mounted display of the user) and object-anchored (panel anchored to the object associated with current content) - in the VR environment with forty-two participants in the context of learning how to operate a laser cutting machine through an immersive tutorial. In the follow-up study, twenty-two participants from this study were given the option to choose from these four placements to understand their preferences. The effects of placements were examined on learning outcome measures - knowledge gain, knowledge transfer, cognitive load, user experience, and user preferences. We found that participants preferred user-anchored (controller condition) and object-anchored placement. While knowledge gain, knowledge transfer, and cognitive load were not found to be significantly different between the four conditions, the object-anchored placement scored significantly better than the TV screen and head-mounted display conditions on the user experience scales of attractiveness, stimulation, and novelty.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Interaction design—Empirical studies in interaction design

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1 Introduction

Recently there has been a surge in the use of Virtual Reality (VR) as a medium for developing learning environments [32]. One of the most important characteristics of a learning environment that illustrates its quality is its ability to achieve the requisite pedagogical goals [36]. Therefore a crucial aspect to take care of while envisioning VRLEs is to focus on their design and development such that they aid learning [27]. Research around the development of efficient and effective VRLEs is still in a growing phase. The instructional design decisions are mostly made on practical or economic considerations rather than evidence-based research resulting in technology-centered rather than learner-centered VRLEs [32]. Due to these minimal guidelines and frameworks [9] majority of the VR applications being developed currently are direct translations of existing educational materials [26].

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The placement of learning content in a virtual learning environment to enhance its noticeability and efficient processing is one of the important design aspects designers need to consider while creating them [49]. VR provides a variety of unique affordances (like multimodal interactions, haptic feedback, and 3D spatial representational capacity) [9] and constraints over 2D digital learning environments for designers to consider [22]. 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 [49]. Nevertheless, 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 [35]. While researchers have evaluated the placement and modality of notifications [22, 24, 46], labels, and subtitles [15, 33, 35, 45, 47, 49] in VR to enhance integration and noticeability, the placement of learning content has not been investigated specifically [49]. 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 [24, 35, 46].

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 [7] 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?

2 Related Work

2.1 Types of Knowledge - Content Classification

To make decisions associated with the presentation of content in any learning environment, first, it is essential to understand the types or classifications of content. A prominent work in this area, The Taxonomy of Educational Objectives by Bloom et al. [11] defines three broad categories of knowledge as knowledge of specifics (declarative), knowledge of ways and means of dealing with specifics (procedural), and knowledge of the universals and abstractions in a field (conceptual). Krathwohl further enhanced the categories defined in Bloom's Taxonomy to add another category, the Metacognitive knowledge [25], which involves knowledge about cognition in general as well as awareness of and knowledge about one's own cognition. Jong has categorized knowledge as generic and domain-specific knowledge, concrete and abstract knowledge, formal and informal knowledge, declarative and procedural knowledge, conceptual and procedural knowledge, elaborated and compiled knowledge, unstructured and structured knowledge, tacit or inert knowledge, strategic knowledge, situated knowledge, and metaknowledge [17]. The learning content strongly determines the type of knowledge being imparted by it; for instance, procedural knowledge is usually disseminated in the form of a set of step-by-step instructions. We place our work around the three main kinds of knowledge discussed by Bloom and set our learning content around these.

2.2 Cognitive Load and Learning

With a surge in the application of VR as a medium for learning, it becomes quintessential to evaluate the effect of immersive VRLEs on learning outcomes. According to the Cognitive Theory of Multimedia Learning (CTML), [34], 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 [44]. 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 [32]. This can lead to improperly designed multimedia environments turning out to be hedonic rather than utilitarian [32]. 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. Therefore, our research agenda follows a learner-centered approach to identify design choices around one of the dimensions of designing VRLEs, i.e., spatial representation to enhance learning, experience and minimize user workload based on the different types of cognitive processing [32].

2.3 Designing VR Environments

Recent research has determined certain design aspects of immersive environments, primarily focusing on textual, modal, spatial, and pedagogical agent representation.

To understand the effect of different modality representations in VR, Ghosh et al. conducted empirical evaluations of the noticeability and perception of 5 different VR interruption scenarios (Person Talking, Incoming Call, Slack pop-up, Person in room, Time spent) across 6 modality combinations (e.g., audio, visual, haptic, audio + haptic, visual + haptic, and audio + visual) [22]. Baceviciute et al. evaluate the translation of the redundancy principle of 2D multimedia environments [38] to 3D VR environments by presenting the same information in three different formats (textual, auditory, and a combination of both). Another work from the same research group further evaluates the effect of content representations for written and spoken information on the process and outcomes of learning [8].

Researchers have further explored various textual representation parameters for designing VR environments. 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 [19].

For pedagogical agent representation, 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 [12, 51]. Petersen et al. [42] discuss the effect of the appearance and behavior of pedagogical agents on knowledge gain.

With respect to spatial representation, most of the research work has been focused on the representation of real-world notifications and information in immersive virtual worlds. 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 [46]. 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) [24]. 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 [15]. 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 [45]. 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 [47]. Mathis et al. introduce the concepts of wall, below-screen, and egocentric messages to convey them to users during TV viewing experiences [33]. 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 [35]. Dominic et al. considered the effects of screen-fixed vs. world-fixed virtual annotations on performance during a navigation task in virtual reality [20].

Unlike textual and agent representation, where some work has been done around educational 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. Previous works have therefore used techniques like the dual-task paradigm where the effects of placements are calculated on a secondary task while the user is working on a primary task [24,46]. Our work, on the other hand, evaluates the effect of these placements when the content is associated with the primary task at hand, i.e., learning. Additionally, in contrast to metrics evaluated in previous research, like noticeability, understandability, intrusiveness, and urgency, we extend these works in the context of learning content by evaluating the effects of these placements on learning outcomes, cognitive load, and user experiences to promote improved learning.

2.4 Learning Content in VR

Recent advances in technology have led to an increased application of VR in the field of education. The use of VR in education started mainly in the fields of aviation and medicine with the advent of VR simulations for flight training and procedures like laparoscopy. Yavrucuk et al. [54] built an HMD-based helicopter simulator to test the viability of virtual reality training for low-cost flight simulation. Hamilton et al. [23] evaluated the effect of VR training on psychomotor skill development for benchtop laparoscopy. Loukas et al. [30] also developed and evaluated a VR simulator LapVR for training basic laparoscopic skills like peg transfer, cutting, and knot-tying. The application of VR further extended to areas like safety training and training of security personnel. Buttussi et al. [13] evaluated HMD-based VR's effects on aviation safety procedures training. Bertram et al. have discussed the use of virtual training environments to train police personnel for complex collaborative tasks [10]. Pallavicini et al. discuss the development of effective stress training programs for military personnel, including soldiers, pilots, and other aircrew professionals [40]

Recently, the development of VR-based education environments has extended toward teaching abstract concepts and factual and conceptual content. MolecularStudio teaches molecular biology, specifically protein structures, to students through VR-based playing [31]. Wang et al. propose a high-fidelity interactive surgical simulator to teach the procedure of Catheter ablation for treating Atrial fibrillation [52]. The Anatomy Builder VR program imparts anatomy education, teaching canine anatomy wherein users identify and assemble bones in the live-animal orientation [50]. Alhalabi et al. discuss the application of VR in engineering education [5]. The Appalachian Tycoon game lets players increase environmental awareness through a fun game in an environmental science class [55]. Detlefsen et al. describe a VR application to teach astronomy to middle school children [18]. Woodworth et al. [53] have explored virtual reality for virtual field trips and guided exploration in the context of a solar thermal power plant. VR is also being explored for teaching computer science concepts to students [43]. On the commercial front, Labster [2] has developed VR simulations for learning subjects ranging from Chemistry, Biology, and General Physics to Engineering, Earth, and Space science.

Apart from this, VR is also being applied for language and culture training. Garcia et al. [21] demo a VR application for learning Spanish, which allows users to explore and interact with their surroundings while exploring Spanish translations of everyday items. Cheng et al. [14] adapted a 3D Japanese learning game Crystallize to VR for teaching embodied cultural interactions like bowing. The Magic Cottage is a VR environment developed for primary school students to enhance creativity in imaginative writing by providing them with an interactive 3D environment with numerous features to act as settings in which their stories could take place [41]. Moesgaard et al. describe a museum learning experience using VR to visualize historical places like Mosede Fort in Copenhagen, Denmark [37].

Even though literature shows a surge in the use of VR for developing learning environments, almost all these environments present learning content in a fixed position in the VR environment without taking into account the variety of affordances VR offers in terms of spatial representation. We have therefore identified these four possible content placement options and evaluated them on various learning measures to develop more effective VRLEs.

3 Research Methodology

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.

3.1 Experiment 1- Spatial Representation Effect Study

3.1.1 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 representing the three types of spatial representations, comprised 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.

3.1.2 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.

3.1.3 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 [22, 24, 46], the controller-anchored placement was designed like a smartwatch. 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 [24, 46]. 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 [35] 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.

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.

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

Table 1: Participant Demographics Table

3.1.4 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 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.

3.1.5 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) [39], intrinsic cognitive load using a measure from Ayres (2006) [6], extraneous cognitive load using a measure from Cierniak et al. [16] and perceived concentration during learning using a measure from Salomon [48]. All items were reported on a 9-point Likert scale. A 10-item cognitive load instrument discussed by Leppink et al. [28] 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 [3] test to assess the workload experienced by participants while experiencing the virtual environment in all four conditions.

User Experience: The UEQ (User Experience Questionnaire) [4] 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).

3.1.6 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 [1]. A summary of the findings for all the measures can be found in Fig. 2.

Learning Assessment: We employed two learning-outcome measures - Knowledge Gain and Knowledge Transfer. Parametric analyses using one-way ANOVAs were applied. Fig. 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 = 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 [6,16,39,48] were analyzed using the parametric one-way ANOVA tests. Fig. 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 [28] 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 Fig. 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 Fig. 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).

3.2 Experiment 2 - User Preferences Study

3.2.1 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.

3.2.2 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

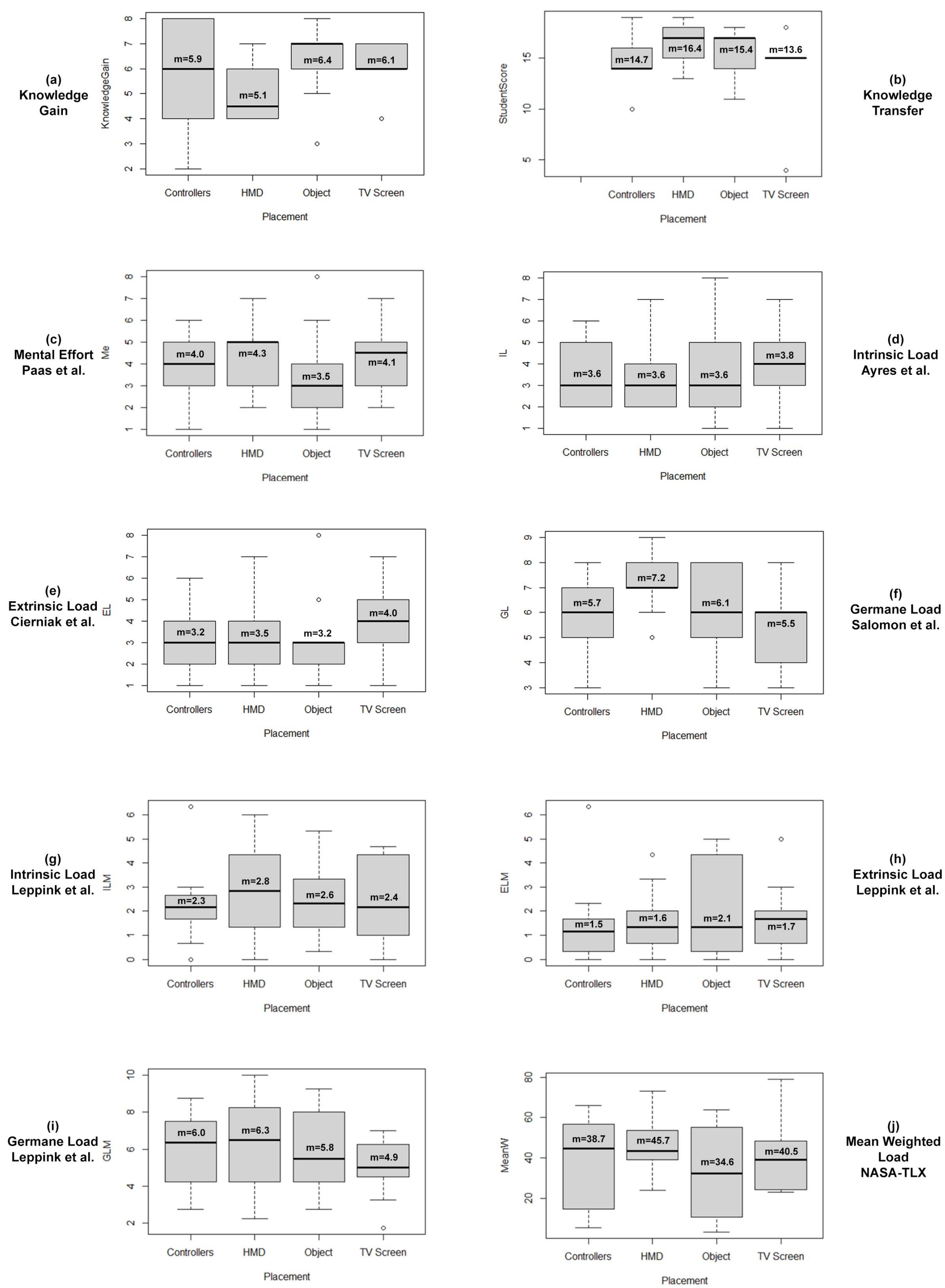

Figure 2: Box plots for Learning Outcomes and Cognitive Load Findings (the horizontal black line denotes Median and 'm' denotes mean values)

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.

3.2.3 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

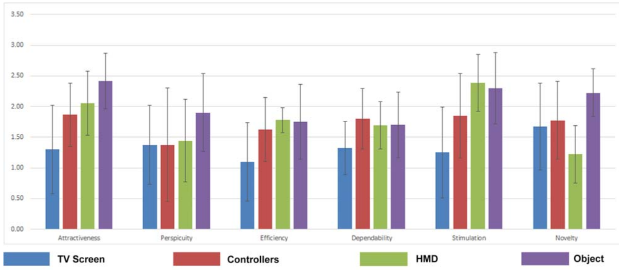

Figure 3: User Experience Scale-Means for the four placements of learning content

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.

3.2.4 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).

3.2.5 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 placements 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.

3.2.6 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. Maximum 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."*

4 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 [6, 16, 39, 48], the validated Leppink et al. instrument [28] and the NASA TLX load index [3]. 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. [46], 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 [35] 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. [46] 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 [29] 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., [46], 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.

5 Conclusion and Future Work

In this research work, we evaluated the effect of four placements of learning content in VRLEs on learning outcomes, cognitive load, user experience, and user preferences around these placements. We found that users distinctly preferred user-anchored (controller-anchored for procedural and HMD-anchored for factual and conceptual content) and object-anchored placement of learning content. We also found the object-anchored placement to be leading in terms of user experience on the scales of attractiveness, stimulation, and novelty. Our results provide recommendations for design decisions associated with spatial representation in VR for factual, conceptual, and procedural learning content. We did not find significant effects of these placements on learning outcomes and cognitive load measures. However, result patterns motivate the pursuit of these factors in more detail, with higher variability in participant demographics and different types of learning contexts. As VR devices become more prevalent and with the democratization of learning, we expect an increase in the use of VRLEs for educational and training purposes, thereby making it interesting to be extended in this variety of contexts.

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