Human-centered design of VR interface features to support mental workload and spatial cognition during collaboration tasks in manufacturing

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Abstract

Industry 5.0 revolution is prioritizing human-centricity and adapting technologies to augment shopfloor workers' cognitive ergonomics. To provide a user-friendly, efficient virtual planning tool, virtual reality (VR) is adopted by the industry to provide a virtual work environment for layout planning, design reviews, and training use cases. However, the user interface (UI) of VR programs is not yet standardized for universal design, and thus causes issues such as difficult scalable technology adoption due to high mental workload. Creating intuitive and accessible interfaces is a key challenge in VR. As the complexity of VR platforms grows, it is vital that users can effectively explore and engage with them. Improved UI design may improve the whole user experience, making VR more accessible, scalable, and attractive to a larger audience. Navigation in a VR environment can impose a significant mental workload on users, affecting their cognitive capacities, including layout perception, navigation, attention for collaboration, and response/completion time. This study aims to identify and assess the UI design features of a virtual work environment for manufacturing regarding mental workload, spatial navigation, and performance-based evaluation for human centricity. Three design features of typical mini maps examples, which are extracted from the literature and the gamification industry, are portability, tangibility, and dimensionality. By identifying the association between design features and user navigation experience, we may observe patterns for broader VR user interface standardization that address human factors. This study employed a qualitative approach to assess five different prototypes of interactive map designs, categorized into three design features, involving both students and industry practitioners, and resulting in 114 valid data collection sessions in the prototype-based experiment. Reducing mental workloads in VR interfaces can increase efficiency and user satisfaction in Industry 5.0 through intentional use of specific design features—portability proved to have the most significant impact, consistently reducing mental, physical and temporal demands, and frustration, while simultaneously improving performance, layout perception, navigation, and collaborative efficacy. The study provides effective design feature identification, highlighting the importance of user-centric approaches in VR development for cognitive ergonomics.

Keywords VR · User interface design · Mental workload · Industry 5.0 · Assisted navigation · Mini maps · Cognitive ergonomics · Collaborative manufacturing

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1 Introduction

Industry 5.0 is to create a more harmonious relationship between humans and technology in order to address the challenges and issues that arise from the increasing reliance on automation and digitalization (Loizaga et al. 2023). Industry 5.0 seeks to promote worker well-being and establish sustainable, resilient systems through human-centered strategies that incorporate virtual reality (VR), artificial intelligence (AI), robotics, and digitalization (Alves et al. 2023). However, interactive systems in manufacturing automotive industrial settings have yet to catch up with consumer products in terms of quality of interaction and user experience (Mucha et al. 2018). In the era of Industry 5.0, mental workload optimization provides opportunities to boost the performance and efficiency of shop floor workers, and also enhance collaboration, well-being, and work satisfaction (Geurts et al. 2022). VR systems represent innovative solutions that blend technological advancements with human-centric design to align with Industry 5.0 principles (Escallada et al. 2025). Despite the growth and development of VR technologies and hardware devices, if a VR-based task is not designed with an appropriate level of mental workload to match the users' expertise, the task performance and technology utilization may be restrained (Zhang et al. 2016). This study, therefore, aims to bridge the gap between cognitive ergonomics of VR technology adoption and universal design of human–computer interaction (HCI) in manufacturing contexts, with a particular focus on navigational aids for virtual layout planning in a collaborative manufacturing setting.

Industrial designers prefer virtual workshops and intelligent environment concepts for defining product form, with immersive environments and rapid project switching being preferred (Sener and Wormald 2007). VR is a key technology in this transformation, supporting various aspects such as layout planning, design reviews, virtual prototyping, machine/robot interaction, ergonomics assessment, and virtual training (Cao et al. 2023). This approach to improve the cognitive ergonomics of the UI of VR applications aims to align technological advancements with human needs and capabilities, promoting efficiency, effectiveness, and satisfaction in the manufacturing process.

In multi-user VR settings, the concept of a spatial navigation visual aid called "mini map" (Cao et al. 2024) can serve as an important navigation assistance, supporting users in navigating complex virtual environments efficiently. This is especially true in manufacturing engineering, where tasks such as factory layout planning, design reviews, and real-time collaboration with multiple stakeholders in complex virtual environments are needed. Mini maps provide a structured visual representation of the virtual space, enabling users to process information quickly and make informed decisions. Computer-integrated simulations using virtual prototypes and digital human models can optimize workstation design and validate design alternatives before creating the final product (Peruzzini et al. 2019). The seamless integration of mini maps within VR platforms is crucial for reducing mental load and improving both operational accuracy and speed, aligning with the human-centered goals of Industry 5.0 (Zalozhnev and Ginz 2023). This paradigm shift towards more personalized and human-centric manufacturing processes calls for innovative methods to reduce mental workload and enhance decision-making through better user interface design (Skulmowski and Xu 2021).

Navigating in VR environments can impose a significant mental load on users, affecting their mental functions such as short-term memory, attention, perception, and response time (Han et al. 2021). Increased mental workload in immersive virtual reality during visuomotor adaptation is related to decreased long-term motor memory formation and context transfer (Juliano et al. 2021). Increasing mental load in VR users leads to an increase in relative pupil size and fewer fixations, among other eye behaviors (Schirm et al. 2023), thus affecting attention. This increased mental workload can lead to various challenges, impacting VR applications' overall user experience and effectiveness.

Studies suggest that users often experience higher mental workload during complex motor tasks in head-mounted displays (HMD) compared to traditional computer screens (CS) (Bernal et al. 2024). Increased cognitive and affective load in virtual reality navigation can decrease navigational performance (Parsons et al. 2023). VR environments can significantly alter mental workload dynamics. These mental load factors will thus negatively affect the collaborative activities in the virtual environment, like layout planning, design reviews, and remote assistance, if no measures are taken. It is crucial to effectivity leverage user cognitive psychology and design features during the VR scene design phase, in order to improve the efficiency of information acquisition and task execution in VR, enhance user experience, and reduce cognitive load for users (Fu et al. 2024). However, research on measures to optimize mental workload in VR is lacking, especially in the standardization of UI universal design for virtual navigation.

This study aims to answer the following research questions:

RQ1: *What visual navigational aids exist in VR games or literature, and how can they be evaluated in a manufacturing context using a prototype-based test for mental workload assessment?*

RQ2: *How do differently designed features of mini maps affect the users' mental load and spatial cognition during navigation in a manufacturing context?*

The design of VR interfaces can either alleviate or exacerbate extraneous mental workload, highlighting the importance of thoughtful design in optimizing user experience and performance outcomes (Reiners et al. 2021). The objectives of this paper are to explore the human-centered design approach with a prototype-based experiment, through a use case of an interactive navigational aid—mini map, designed to provide optimized mental load and improve spatial cognition during navigation.

The study demonstrates that special design features in the UI of virtual navigation can significantly influence users' experience of mental workload and spatial capability. Three design features are extracted from variable navigation aids through literature review and the gamification industry, which are portability, tangibility, and dimensionality. Through a prototype-based experiment, the three design features of mini maps are assessed, compared with an ANOVA test and thematic analysis, to identify their different influence on mental, physical, and temporal demands, frustration, performance, effort, layout perception, navigation, collaboration efficacy, and completion efficiency. The result shows that portability reduces overall mental workload significantly compared to tangibility and dimensionality, which indicates that portability could be a potential UI design feature to achieve user-friendly navigation augmentation for layout planning tasks in manufacturing.

2 Theoretical framework

Human-system interaction requires the coordination of perceptual, cognitive, and motor functions (Neumann et al. 2020). In the realm of Human–Computer Interaction (HCI), cognitive ergonomics centers on four main challenges: legacy due to long task completion time, low user satisfaction, high error rates, and long response durations (Cañas 2008). Human factors and ergonomics research can optimize overall system performance and human well-being in the context of manufacturing industries (Reiman et al. 2021). The exploration of HCI in VR for educational and business purposes is a dynamic field, with ongoing research focusing on the complex interplay of technology, user experience, and use cases (Li 2024).

Mental Workload can be defined as "the ratio of demand to allocated resources" (Luong et al. 2020). It is an essential metric for evaluating the impact of performing tasks and predicting operators' performances and technology adoption (Cain 2007). Optimizing mental workload has been proven to reduce human errors, improve system safety, increase productivity, and enhance operators' satisfaction

with their working experience (Luong et al. 2020). Mental workload can be measured in multiple ways, including subjective (or self-report), physiological, and task performance measures (Fogelberg et al. 2024). Self-report methods can be categorized into multidimensional or unidimensional scales (Luong et al. 2020). One of the most recognized and commonly used standardized multidimensional scales is the NASA-Task Load Index (TLX) (Hart and Staveland 1988). Performance measures mainly depend on the type of task, and error rate and completion time are the common measures (Fogelberg et al. 2024). The physiological measures can be assessed through signals like electroencephalogram (EEG), pupillometry, heart rate variability (HRV), etc. (Tao et al. 2019), but this will not be the focus of this study due to the scope.

VR tends to have a higher mental fatigue rate compared to conducting the same tasks in a real-life situation (Vasilev et al. 2018). Besides, VR induces a higher mental workload than PC (Matsuura 2019; Souchet et al. 2023). The high mental workload can result in fatigue, stress, or affective states in other contexts, measured by psychological or physiological assessment (Luong et al. 2020). Some researchers observed that although VR environments can provide an immersive experience, they may also lead to higher mental workload and attention dispersion among learners, ultimately affecting the learning outcomes and user experience (Makransky et al. 2017), which may be due to HCI interfaces (Hou et al. 2025).

There are existing guidelines considering mental overload factors in VR, which are the time pressure and task difficulty (Souchet et al. 2023). The literature review conducted by Souchet et al., has concluded that basic interaction and interface can influence task difficulty, and has come up with guidelines for testing interfaces to avoid unnecessary working memory solicitations by NASA-TLX, adapting interactions and interface based on the user's characteristics or preferences. However, these guidelines lack empirical study to validate these principles, and also the design features have been ignored, which could be useful as a foundation for universal design, particularly in the automotive industry, where VR use cases are emerging. A simple Egocentric interface considerably improves visual search efficiency and navigation performance in immersive network exploration (Sorger et al. 2021).

Despite the importance of the navigational user experience of self-report added on mental workload assessment, there remains a lack of consensus on how to define "spatial cognition" (Thorp et al. 2024). As a concept, "spatial cognition" encompasses a wide array of tasks, including (but not limited to) spatial memory, spatial orientation, spatial visualization, and spatial perception (Uttal et al. 2013). This was achieved through a recall experiment to assess the accuracy of memory. Designing XR experiences requires a

comprehensive understanding of spatial cognition, which refers to the mental processes involved in acquiring, organizing, and utilizing knowledge about spatial relationships between objects (Zhao et al. 2023). Areas of interest for researchers are the design and allocation of visual cues on mobile maps (Cheng et al. 2022). There are many aspects that have been investigated regarding spatial navigation in virtual environments. High-fidelity 3D rendering in mobile applications, involving spatial cues, is essential for delivering immersive user experiences in extended reality (XR) (Estey et al. 2022). Research on navigation assistance user interfaces exists, like 2D or 3D, but studies specifically examining mental load and mini map design features on portability and tangibility are lacking. This study will focus on addressing that gap and compare the significance of design features in decreasing mental workload.

3 Methods

Section 3 provides an overview of the prototype development process, and the subsequent experimental setup used to investigate various mini map designs in a multi-user VR environment. The Methods part is to answer the **RQ1**: *What visual navigational aids exist, and how can they be evaluated in a manufacturing context using a prototype-based test for mental workload assessment?*

It begins with a literature-based identification of different map categories, followed by the creation of five distinct prototypes with unique UI features. These prototypes were implemented in a virtual factory scenario, allowing participants to collaborate on a gamified maintenance task. The section then describes the study's participant groups, experimental procedures, and the assessment methods

employed—both quantitative (NASA-TLX and spatial cognition measures) and qualitative (survey responses and thematic analysis). Through this integrated methodology, Sect. 3 sets the stage for understanding how design attributes such as portability, dimensionality, and tangibility affect user experience, mental workload, and navigation performance.

3.1 Prototype development

The whole design and experiment process is illustrated in Fig. 1. Firstly, a literature search was conducted to define the existing and explored spatial navigational aid using mini maps in VR as shown in Table 1. It was found by the reviewed literature that a total of three main design features (Portable vs Non-portable/Tangible vs Non-tangible/2D vs 3D) have historically been used in various combinations, making up a total of five different mini map concepts, after which the authors saw a saturation in the literature. Representative examples from literature illustrating the five unique concepts (Horbinski and Zagata 2022; Badr and De Amicis 2023; Kuo et al. 2022; Lee et al. 2022; Hou et al. 2021) can be seen in Table 1. All the five concepts are unique in their design and provide various levels of interaction and capabilities. Their ability to affect spatial learning and navigation in a virtual space is the subject of this study. Each of the potential mini map concepts were taken forward into the prototype development. In order to evaluate the different minimap concepts, a small, gamified scenario was created within a multi-user VR platform. Where participants, divided into pairs, collaborated in solving tasks in an Over-Maintenance puzzle game, inspired by Overcooked (Ghost Town Games, UK), a cooperative game where players collaboratively tackle tasks under time constraints. Using the different versions of the mini maps as navigational aids, they
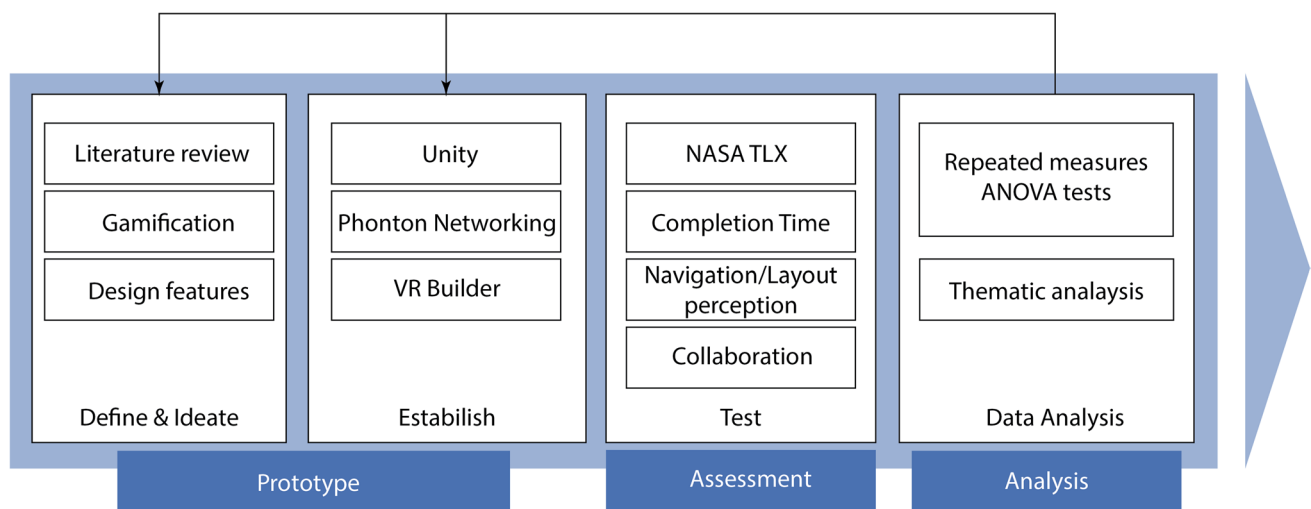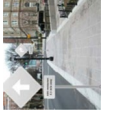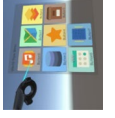

Fig. 1 The design and experiment process of the prototype-based experiment study

Table 1 Outlines the different mini map categories that were implemented in the software. The last row of the table shows how the different mini maps were implemented in the experimental software

Mini map	A	B	C	D	E
Description	Hand-held map attached to the VR controller	Hand-held "dollhouse" attached to the VR controller	Static 2D GUI map in the corner of the FOV	In world navigational objects	Toggleable UI window map
Detailed description	2D top view map displayed on an 3D object in the virtual world attached to the VR controller (e.g., mobile device, paper map)	A 3D miniature version of the facility or environment (i.e., dollhouse) attached to the VR controller	Static 2D top view map attached to the peripheral or corner of the display. Frequently used in desktop gaming applications	Navigational objects and maps added as static objects in the VR environment (e.g., 3D signs or site maps)	Toggleable UI window in front of the user containing a 2D top view map. Commonly used menu interface in various VR applications
Reference Example from Literature reviews	(Kuo et al 2022)	(Horbinski and Zagata 2022)	(Badr and De Amicis 2023)	(Lee et al 2022)	(Hou et al 2021)
Developed demonstrator and its design features	Portable 2D Tangible object	Portable 3D Tangible object	Non-portable 2D Non-tangible object	Non-portable 2D Tangible object	Portable 2D Non-tangible object

were asked to cooperate and carry out a series of tasks while measured on their performance.

The gamified multi-user VR experience was developed using the Unity 3D Game Engine (Unity 2023) and the available Photon Networking (PhotonEngine 2023) plug-in for Unity, allowing for multiple participants to collaborate in a shared VR environment. Furthermore, the VR Builder (MindPort 2023) plug-in to Unity was utilized enabling VR interactions and VR task sequencing in the shared virtual environment. To facilitate collaboration and interaction between players in the shared virtual world life size virtual avatars were added representing each participant. Furthermore, a virtual model of a factory was introduced creating immersion of the manufacturing context as well as providing a complex layout for the participants to navigate within. Finally, the concepts of the five mini maps were developed and added to the multi-user VR platform as the subject of navigational aid to assess within the VR environment. Each of the mini maps developed indicated the locations of each participant in real time, in relation to the factory layout plan, as well as move markers or indications of where in the factory to move in order to carry out the tasks as part of the gamified experience.

3.2 Participants

A purposive sample of participants (Palys 2008) was recruited, where the intention was to seek out people with a comparable level of experience with manufacturing contexts and/or VR use. The study's participants belonged to two distinct groups: students and industry practitioners, who were chosen to reflect a wide variety of experiences relevant to VR interface usability in the context of mini map design.

Test group 1—students: The student group consisted of 18 students from Chalmers University of Technology, with a balanced gender representation to encourage gender equality in study outcomes. These individuals, who were relatively new to the subject of VR, were mostly studying Production Engineering. They were picked since they were inexperienced with complex VR apps, since the study aimed to explore how straightforward the mini map interfaces are for new users.

Test group 2—industrial practitioners: This group consisted of 12 male volunteers, each approximately 40 years old, with extensive technical expertise, mainly in the automotive and aerospace sectors. These individuals are used to utilizing digital tools such as simulations and have various levels of knowledge of VR technology and gaming, which may impact how they engage with the mini map. Their vast knowledge of digital technologies sets them apart from the undergraduate group, providing insights into how experienced practitioners interact with new XR interface designs. As seen from Fig. 3, they were divided into 6 pairs to try

5 randomized prototypes of the mini map in this study and contributed to 60 validated data collection sessions.

Both groups were chosen at random and consented to participate in this study, guaranteeing that the sample is random and that the study outcomes are generalizable across similar situations. The two groups reflect the common perception of academic and industrial users that virtual tools are necessary for practice and education. Overall, 114 validated data collection sessions were collected and merged for the data analysis.

3.3 Test procedures

The experimental procedure, illustrated with Adobe Illustrator, as shown in Fig. 2, involved multiple iterations and comparisons across different mini map designs. Participants were either students or industrial practitioners and were asked to interact with either three or five mini map prototypes, depending on their group. The order of map presentations was randomized to mitigate potential biases from first trials. Participants were paired to collaborate, ensuring that the interaction and navigation tasks required teamwork and communication.

- *Step 1:* The student group was divided into nine pairs. Each pair tested three randomized mini map prototypes, resulting in 54 valid data collection sessions that captured both mental workload and spatial cognition measures. Similarly, the industrial practitioners were divided into six pairs, each testing five randomized mini map prototypes, providing a separate 60 set of validated data collection sessions.
- *Step 2:* Each pair was tasked to collaborate in solving a simple maintenance task while navigating a factory environment using the different mini maps, while being assigned either the role of a warehouse worker or a machine operator.
- *Step 3:* The warehouse worker in each pair used the mini map to locate a highlighted shelf in the virtual factory, retrieve a spare part, and deliver it to a machine operator stationed across the factory floor. Both participants relied on the mini map to locate each other, coordinate the hand-over, and complete the installation task on the correct machine. After finishing a task, participants took a short break, completed a brief survey, and then repeated the procedure with a different mini map prototype and an updated task layout. Figure 3 shows one example of the task setup and highlighted objectives.
- *Step 4:* Beyond the main experiment, participants completed surveys with both quantitative and qualitative questions to gather subjective assessments of mental workload, spatial cognition and navigation performance. In-depth interviews supplemented the surveys,

Fig. 2 Experimental procedure for students and industrial practitioners
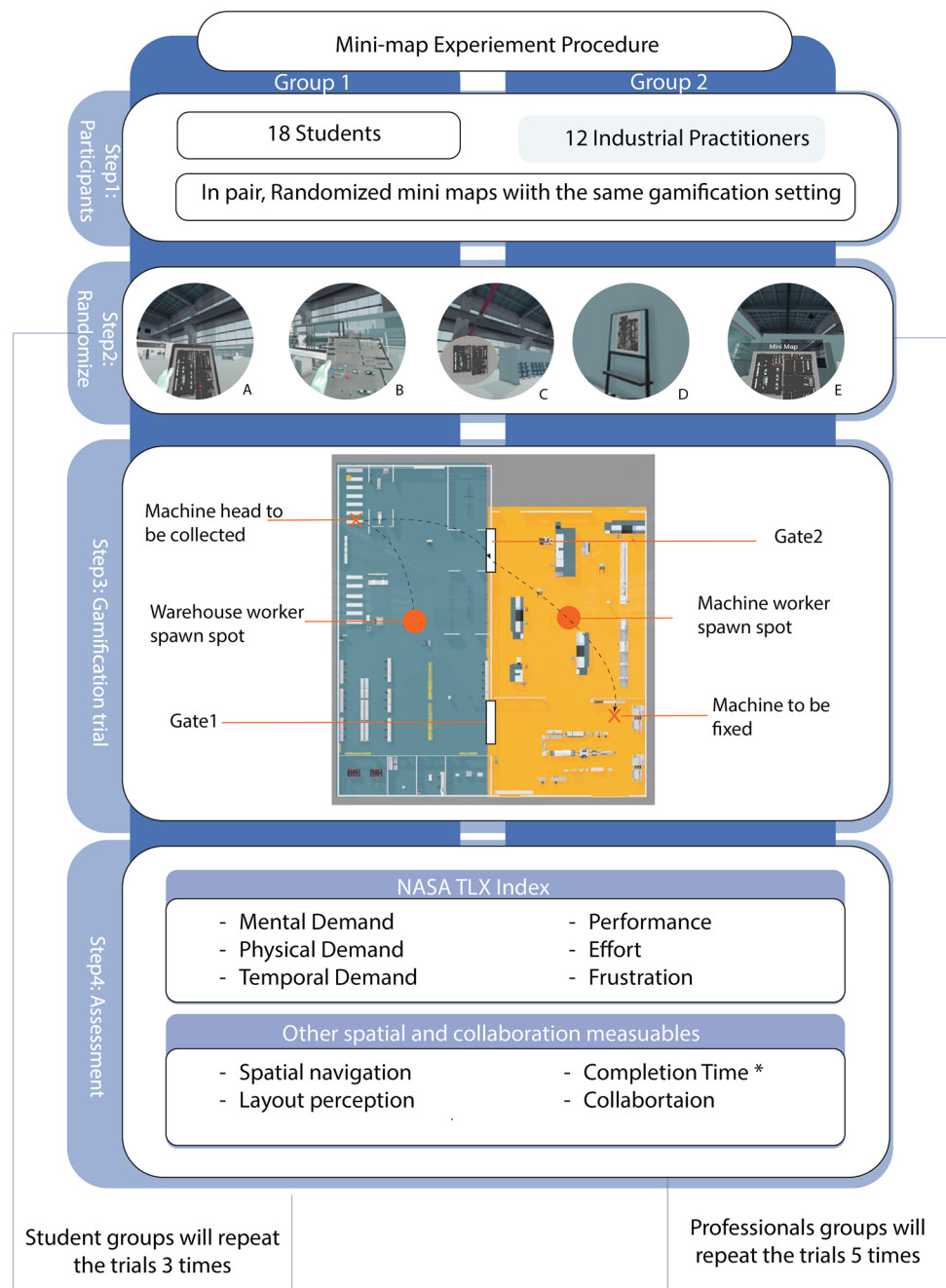
providing richer insights into users' intuitive experiences with each mini map design. This qualitative data helped to contextualize the quantitative results, offering a more comprehensive understanding of how various design features influenced the user experience.

3.4 Assessment method

To obtain perceived workload estimations for the VR mini map designs and to gauge the spatial cognition experience and effectiveness of the proposed interfaces, the widely recognized NASA TLX for mental workload assessment, while a survey questionnaire on the three metrics: spatial
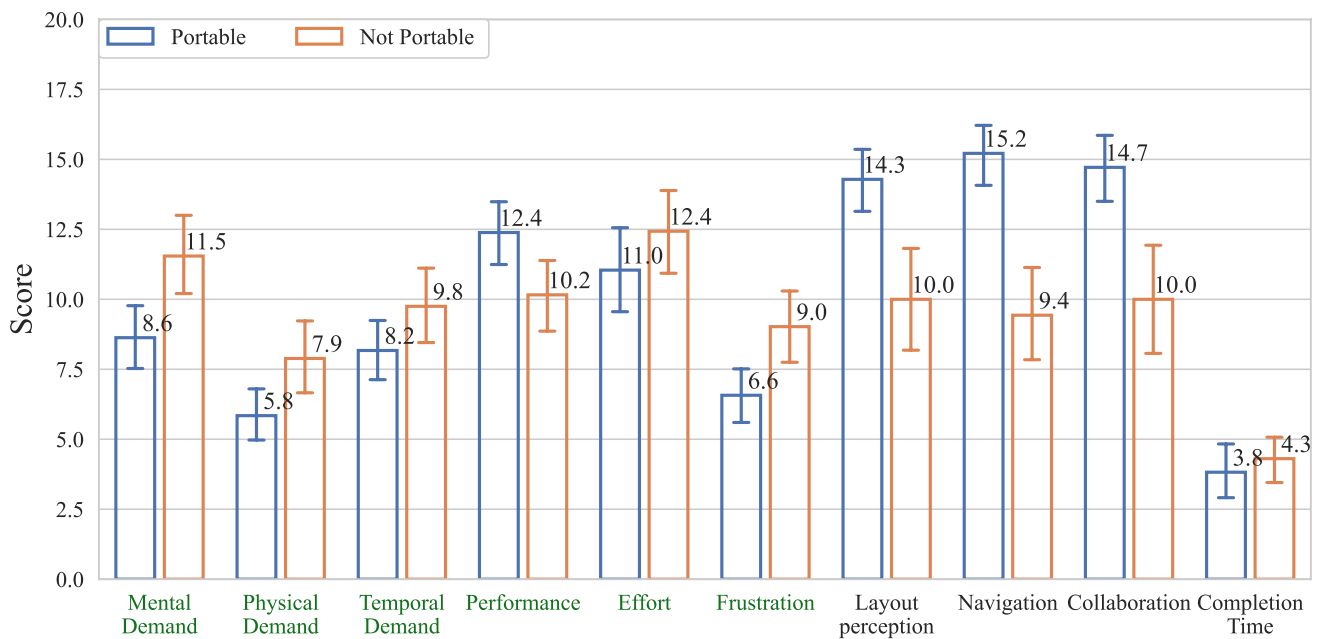
Fig. 3 Mean normalized scores for NASA TLX and spatial cognition metrics with 95% confidence interval under portable vs. not portable

navigation, layout planning, collaboration with Likert scale (e.g., 1 = very poor, 5 = excellent), and completion in seconds. These scores are considered quantitative data because we assign numerical values to responses, enabling calculations like mean, median, and standard deviation.

NASA-Task Load Index (NASA-TLX; Hart and Staveland 1988) was employed in its raw (unweighted) form via a software-based questionnaire (Hart 2006). The modified raw NASA-TLX questionnaire is a reliable tool for measuring subjective workload in monitoring tasks (Said et al. 2020). The software version of the NASA TLX simplifies collection, postprocessing, and storage of raw data for assessing subjective mental workload (Cao et al. 2009). The NASA-TLX captures six subscale categories—cognitive demand, physical demand, temporal demand, performance, effort, and frustration—each rated immediately after the task on a scale from 0 (low) to 20 (high), except for performance which is scored inversely (0 being good and 20 being poor). In this study result, the performance score has been reversed to increase the readability. This combination of quantitative ratings and qualitative feedback provides valuable insights into user experiences with different prototypes, enabling a thorough assessment of how effectively each mini map supports user navigation and engagement within the VR environment.

While the NASA-TLX is sensitive to varying levels of user experience (Barajas-Bustillos et al. 2023), it is not entirely without limitations, as participants must retrospectively recall their experiences. Nevertheless, when integrated with user responses gathered from prototype testing, A/B testing, and open-ended feedback, these workload assessments offer a richer understanding of the mental workload dynamics in VR settings. In this study, using the NASA-TLX for both industrial practitioners and students provided a broader perspective on user-centric design considerations and helped identify features that may optimize interface usability and reduce mental workload.

3.5 Analysis methods

3.5.1 Mixed effect modelling for complex experimental designs

Mixed effects modelling offers particular advantages for our study design, as it accommodates the hierarchical nature of our data, where participants worked in pairs and experienced unbalanced conditions of trying mini maps. The mixed effects modeling provides an ideal framework for our study as it combines the strengths of both fixed (design features) and random (user type variability) effects analysis, accommodating the nested structure of our data where observations were collected from participants working in pairs, creating inherent dependencies (Detry and Ma 2016). As noted by Moseley et al., "Mixed models can accommodate unbalanced data patterns and use all available observations and patients in the analysis" (Detry and Ma 2016), which is particularly valuable given the different sample sizes, measurement quantities, and VR experience backgrounds between student and industrial practitioner groups.

Statistical analyses were implemented using Python for the mixed design ANOVA calculations. The significance

level (type I error) was set to 0.05 (Di Leo and Sardanelli 2020). To examine the impact of mini map design features on mental workload and spatial cognition, we employed a mixed-design ANOVA approach that accommodated our unique experimental structure with different participant groups experiencing varying numbers of mini maps. The analysis accounted for our unbalanced design where industrial practitioners (n = 12, 6 pairs) experienced all five mini map prototypes (contributing 60 valid data collection sessions), whereas students (n = 18, 9 pairs) encountered three randomized mini map prototypes (contributing 54 valid data collection sessions). Although NASA-TLX scores are formally discrete ratings, they were treated as continuous data in accordance with common research practice, enabling the application of parametric tests.

For each analysis, we tested both within-subjects factors (design features: portability, dimensionality, and tangibility, as shown in Table 2) and between-subjects factors (student vs. practitioner groups). The statistical analysis determined whether there were significant differences in mean scores for NASA-TLX indices (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration) and spatial cognition measures (Layout Perception, Navigation, Collaboration, and Time) attributable to the presence or absence of specific design features.

We report p-values to indicate statistical significance, representing the likelihood that observed differences occurred by chance rather than due to our manipulated variables. The mean and standard deviation were calculated for all dependent variables. Additionally, we report partial eta squared ($\eta2$) as our primary effect size measure, following conventional guidelines where $\eta2$ values of approximately 0.01 indicate small effects, 0.06 medium effects, and 0.14 or greater large effects (Cohen 1988).

As shown in Table 2, the study assessed three primary mini map design features as the main independent variables for the ANOVA test:

- **Portability**: The capability of the mini map to be transferred, repositioned, or adapted under changing conditions. This ensures that users can interact with the map flexibly in dynamic VR environments.
- **Dimensionality:** A map rendered as a flat, two-dimensional surface, possessing only length and width. Unlike a 3D model, it conveys spatial information without depth, potentially simplifying the user's navigational interpretation. In this study,
- **Tangibility:** A design feature that replicates the form of a physical, tangible item, allowing it to be visually observed, touched, and manipulated. This approach leverages familiar, tactile cues to enhance user interaction and spatial understanding.

3.6 Thematic analysis

A thematic analysis was conducted on self-reported qualitative data from participants to identify key themes related to their experiences with different mini maps. Participants provided open-ended feedback after completing tasks using portable, 2D, 3D, and Tangible object-based mini maps. The analysis followed the thematic analysis approach outlined by Braun and Clarke (2006) and consisted of five iterative phases.

- Phase 1: Familiarization with the Data: The first step involved becoming familiar with the collected data. Participants were asked to state "three things on top of their mind" regarding their experience with each mini map. The collected data were reviewed multiple times to gain

Table 2 Overview of mini map and their design features

Design features *Definitions*	Mini map A	Mini map B	Mini map C	Mini map D	Mini map E
Portability The capability of being transferred or adapted under changing conditions	✓	✓	✗	✗	✓
Dimensionality A map rendered as a flat, two-dimensional surface, possessing only length and width.	✓	✗	✓	✓	✓
Tangibility A design feature that replicates the form of a physical, tangible item, allowing it to be visually observed, touched, and manipulated.	✓	✓	✗	✓	✗

an in-depth understanding of the feedback and to begin identifying recurring patterns.

- Phase 2: Generating Initial Codes: In this phase, the data were systematically examined to generate initial codes. These codes represented smaller units of meaning within the data, which highlighted the specific advantages, disadvantages, or important features of the mini maps. For instance, examples of early codes included "easy to bring the map into focus" and "hard to toggle the map with the controller". Keywords and concepts related to usability, navigation, visibility, and collaboration started showing at this stage.
- Phase 3: Searching for Themes: The initial codes were then analyzed to identify broader themes that captured the participants' experiences. This involved grouping similar codes into overarching categories. For example, codes related to handling and adjusting the mini map were clustered under the theme of usability, while those concerning locating oneself or others were grouped under navigation. This phase also included identifying repeated keywords and key points across the dataset.
- Phase 4: Reviewing the Themes: The identified themes were iteratively refined and reviewed to ensure they accurately reflected the data. During this phase, the themes were cross-referenced with the raw data to confirm their validity and coherence. For example, the theme of visibility was revisited to incorporate participants' comments on map size, placement, and visual clarity.
- Phase 5: Defining and Naming the Themes: The final step involved defining and naming the themes to provide a clear and concise framework for the analysis. Usability, navigation, visibility, and collaboration were selected as the primary themes, as they consistently captured the key dimensions of participants' feedback.

4 Results

This section presents how various design features of mini map prototypes—focusing on portability, dimensionality (2D vs. 3D), and tangibility, affect mental workload and spatial cognition as measured through the NASA TLX index and task performance indicators. The Results and following Discussion part is to answer the **RQ2**: *How do differently designed features of mini maps affect the users' mental load and spatial cognition during navigation in manufacturing context?*

4.1 Understanding design features and user type differences

For each analysis, we examined the impact of three independent variables (Portable, 2D, and Tangible Object design features) on multiple dependent variables, including NASA TLX indices (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration) and spatial cognition measures (Layout Perception, Navigation, Collaboration, and Completion Time).

The mixed-design ANOVA enables us to:

1. Assess the main effects of each design feature across all participants, identifying universal design principles that transcend user groups
2. Examine potential interactions between design features and user groups, illuminating whether certain features are particularly beneficial for specific user populations
3. Maintain focus on design elements rather than group differences, while still accounting for group-level variance in the statistical model.

5 Mixed design ANOVA test

The mixed design ANOVA results presented in The Table 3 demonstrate the differential impacts of portability, dimensionality, and tangibility on both mental workload and spatial cognition measures. Statistical analysis reveals that portability emerges as the most influential design feature, showing significant effects across 9 of 10 metrics (all $p < 0.05$). Users experienced substantially reduced mental workload with portable mini maps, as evidenced by lower mental demand ($p < 0.001$, $\eta^2 = 0.35$), physical demand ($p < 0.001$, $\eta^2 = 0.27$), and frustration ($p < 0.001$, $\eta^2 = 0.30$). Simultaneously, portability significantly enhanced spatial cognition measures, with particularly strong effects on navigation ($p < 0.001$, $\eta^2 = 0.53$) and layout perception ($p < 0.001$, $\eta^2 = 0.43$).

Dimensionality showed more selective effects, significantly influencing layout perception ($p = 0.03$, $\eta^2 = 0.21$) and completion time ($p < 0.001$, $\eta^2 = 0.41$), with 2D maps enabling worse layout understanding and 3D maps resulting in shorter task completion times. Tangibility demonstrated no significant main effects on any measure, suggesting it may be the least critical design feature among those tested.

Notable user group differences emerged across several metrics. Industrial practitioners consistently reported lower mental demand than students across all design features (all $p < 0.05$), with particularly pronounced differences in effort ratings ($p < 0.001$, $\eta^2 = 0.56$–0.65). Practitioners also completed tasks significantly faster than students regardless of design feature ($p < 0.001$, $\eta^2 = 0.49$–0.76), likely reflecting their professional expertise. However, both groups showed similar patterns of response to the portable feature, suggesting its benefits transcend experience levels and supporting its importance as a universal design principle for VR mini maps.

Table 3 Reveals significant effects of mini design features on mental workload and spatial cognition metrics across user types

Dependent Variable	Independent variable	Mean (SD)				Statistics p(η2)	
		Design feature		User type		Design feature	User type
Metric	Design feature	Without	With	Student	Industrial practitioners	With & without	Student& industry
Mental Demand	Portability	11.55 (4.85)	8.63 (4.7)	12.0 (4.86)	6.33 (4.53)	0.00 (0.35)*	0.03 (0.18)*
	Dimensionality	9.73 (5.2)	9.76 (4.9)	12.57 (3.80)	8.73 (5.29)	0.10 (0.12)	0.01 (0.31)*
	Tangibility	9.61 (4.85)	9.84 (5.04)	11.2 (4.61)	8.25 (5.59)	0.55 (0.01)	0.02 (0.19)*
Physical Demand	Portability	7.89 (4.48)	5.84 (3.79)	8.80 (5.13)	5.36 (4.52)	0.00 (0.27)*	0.25 (0.05)
	Dimensionality	7.12 (4.8)	6.49 (3.99)	8.00 (4.96)	6.06 (4.28)	0.93 (0.00)	0.22 (0.07)
	Tangibility	6.5 (4.42)	6.71 (4.04)	7.20 (4.42)	6.17 (4.29)	0.66 (0.01)	0.53 (0.02)p--
Temporal Demand	Portability	9.75 (4.45)	8.17 (4.37)	9.80 (4.76)	7.33 (4.51)	0.01 (0.26)*	0.40 (0.03)
	Dimensionality	9.0 (4.94)	8.72 (4.32)	10.86 (4.82)	8.65 (4.56)	0.14 (0.10)	0.20 (0.08)
	Tangibility	9.09 (4.83)	8.59 (4.22)	9.40 (5.07)	7.92 (4.44)	0.37 (0.03)	0.56 (0.01)
Performance	Portability	9.84 (4.32)	7.61 (4.96)	10.4 (3.98)	5.36 (4.49)	0.00 (0.33)*	0.03 (0.17)*
	Dimensionality	9.04 (5.18)	8.31 (4.74)	11.43 (4.11)	7.15 (4.93)	0.67 (0.01)	0.02 (0.24)*
	Tangibility	8.82 (4.98)	8.26 (4.75)	10.4 (4.38)	6.61 (4.80)	0.11 (0.10)	0.03 (0.16)*
Effort	Portability	12.43 (5.07)	11.04 (6.55)	15.4 (4.55)	6.36 (4.24)	0.31 (0.04)	0.00 (0.62)*
	Dimensionality	11.38 (6.03)	11.64 (6.07)	15.43 (3.80)	8.08 (4.53)	0.42 (0.03)	0.00 (0.65)*
	Tangibility	11.16 (5.68)	11.84 (6.28)	14.8 (5.04)	7.58 (4.74)	0.66 (0.01)	0.00 (0.56)*
Frustration	Portability	9.02 (4.28)	6.57 (4.05)	8.40 (3.87)	5.78 (4.46)	0.00 (0.30)*	0.63 (0.01)
	Dimensionality	7.85 (4.53)	7.42 (4.24)	8.86 (4.49)	7.44 (4.97)	0.74 (0.01)	0.47 (0.02)
	Tangibility	7.93 (4.58)	7.26 (4.11)	8.00 (3.89)	6.89 (4.66)	0.17 (0.07)	0.86 (0.00)
Layout Perception	Portability	10.0 (6.0)	14.29 (4.98)	11.5 (5.64)	13.89 (4.94)	0.00 (0.43)*	0.15 (0.08)
	Dimensionality	13.65 (5.75)	12.33 (5.77)	12.14 (6.11)	10.94 (5.89)	0.03 (0.21)*	0.87 (0.00)
	Tangibility	11.7 (5.49)	13.21 (5.9)	11.75 (5.68)	11.94 (6.36)	0.15 (0.08)	0.08 (0.11)
Navigation	Portability	9.43 (5.73)	15.21 (4.38)	11.0 (5.53)	15.83 (3.68)	0.00 (0.53)*	0.22 (0.06)
	Dimensionality	14.04 (5.1)	12.67 (5.82)	12.86 (5.79)	12.08 (6.17)	0.08 (0.14)	0.52 (0.02)
	Tangibility	12.73 (5.44)	13.14 (5.85)	12.5 (5.50)	12.64 (6.27)	0.82 (0.00)	0.75 (0.00)
Collaboration	Portability	10.0 (6.56)	14.71 (5.1)	10.75 (6.93)	15.0 (4.63)	0.00 (0.28)*	0.60 (0.01)
	Dimensionality	14.23 (5.78)	12.5 (6.21)	13.21 (6.96)	12.08 (6.26)	0.07 (0.14)	0.86 (0.00)
	Tangibility	11.59 (5.88)	13.71 (6.18)	11.25 (6.26)	13.33 (6.21)	0.41 (0.03)	0.84 (0.00)
Completion Time	Portability	4.31 (2.87)	3.82 (4.24)	6.23 (2.78)	1.57 (1.45)	0.04 (0.15)*	0.00 (0.49)*
	Dimensionality	2.94 (2.01)	4.33 (4.09)	4.29 (1.70)	2.19 (1.78)	0.00 (0.41)*	0.00 (0.76)*
	Tangibility	4.57 (4.87)	3.65 (2.84)	7.34 (5.98)	1.87 (1.70)	0.06 (0.13)	0.00 (0.49)*

With dimensionality means 2D while without dimensionality represents 3D maps

5.1 Empirical evaluation based on the mean value and STD

A series of bar charts (Figs. 3, 4 and 5) display mean scores (normalized to a 0—20 scale) and their 95% confidence intervals for six workload-related metrics (Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration) and four spatial cognition measures (Layout Perception, Navigation, Collaboration, and Time). Statistical analyses (The Table 3) highlight which design features yield significant differences, while a thematic analysis of participant feedback explores underlying user experience factors. Notably, the plots allow one to observe which design features tend to produce higher or lower values for both mental workload and spatial cognition measures. This visual representation provides an intuitive overview, complementing the statistical results and helping to discern patterns in how portability, dimensionality, and tangibility each influence user experience and performance outcomes in the VR environment.

When comparing the Portable and Not Portable conditions (see Fig. 3), the mean scores and their 95% confidence intervals reveal clear cognitive ergonomic advantages for the Portable mini map design. Participants experienced significantly lower levels of mental, physical, and temporal demands, as well as reduced frustration and faster task completion times when using the Portable mini map. For example, average Mental Demand was notably
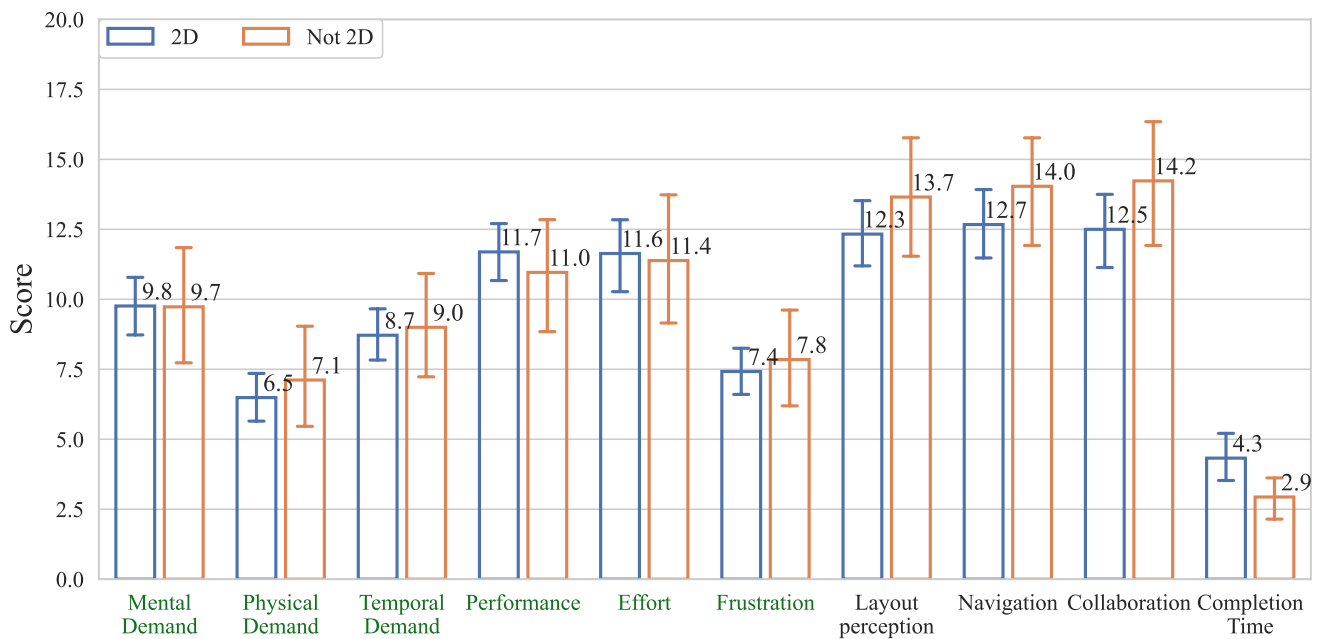
Fig. 4 Mean normalized scores for NASA TLX and spatial cognition metrics with 95% confidence interval under 2D vs. 3D
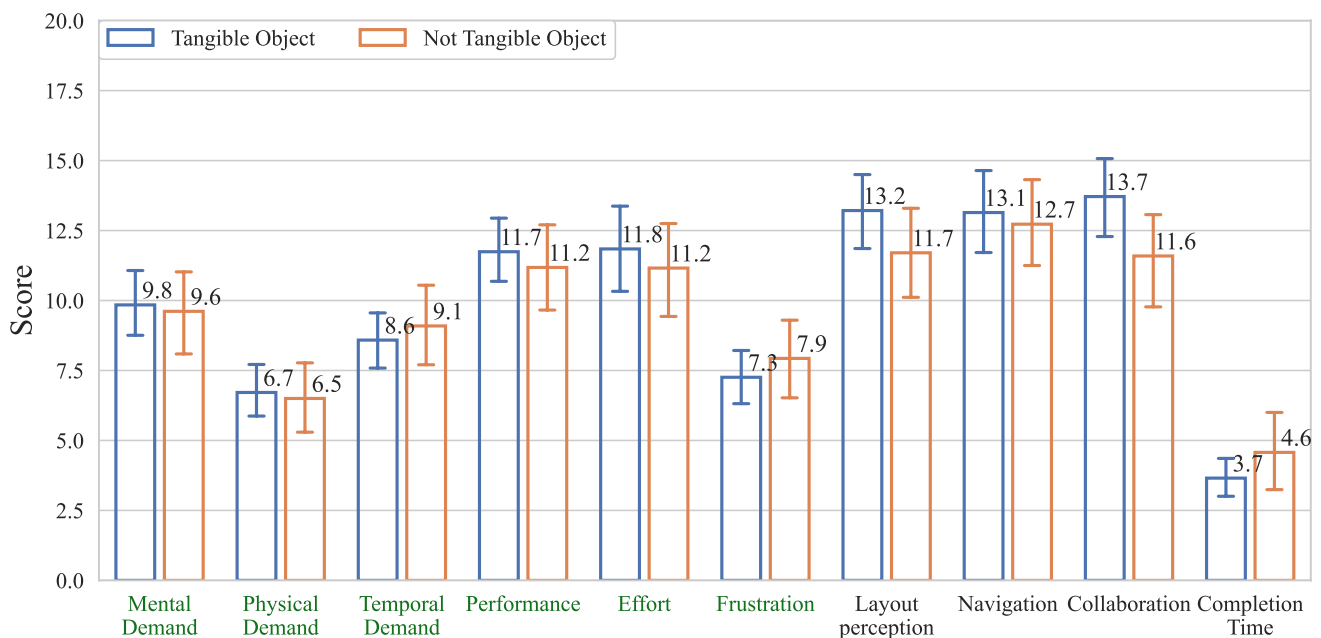

Fig. 5 Mean normalized scores for NASA TLX and spatial cognition metrics with 95% confidence interval under tangible vs. not tangible

lower in the Portable condition (M = 8.63, 95% CI [7.51, 9.75]) compared to Not Portable (M = 11.55, 95% CI [10.07, 13.02]). Frustration scores also decreased with the Portable design (M = 6.57, 95% CI [5.61, 7.54]) versus Not Portable (M = 9.02, 95% CI [7.72, 10.32]). In terms of spatial cognition experience, the Portable mini map led to higher performance, better layout perception, improved

navigation, and enhanced collaboration. For instance, Layout Perception scores increased with the Portable feature (M = 14.29, 95% CI [13.10, 15.47]) compared to Not Portable (M = 10.00, 95% CI [8.17, 11.83]), and Navigation scores were also higher (M = 15.21, 95% CI [14.17, 16.26] vs. M = 9.43, 95% CI [7.69, 11.17]).

Figure 4 illustrates that, under both the 2D and not 2D prototype conditions, the mean values and confidence intervals for Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration remain relatively similar. In other words, introducing a 2D design does not appear to create a significant difference in users' overall workload or performance.

Likewise, as shown in Fig. 5. comparing Tangible Object versus Not Tangible Object conditions reveals overlapping mean values and confidence intervals across all measured metrics. Specifically, Mental, Physical, and Temporal Demands, as well as Performance, Effort, and Frustration, exhibit similar ranges in both conditions. The same pattern emerges for Layout Perception, Navigation, Collaboration, and Completion Time, demonstrating no clear separation of values. Consequently, employing a Tangible Object design does not yield distinctly higher or lower mean scores compared to a Not Tangible Object approach.

6 Thematic analysis

In the thematic analysis, four primary categories emerged: usability, navigation, visibility, and collaboration. Each reflects distinct aspects of participants' experiences with the mini map designs. As shown in Table 4, the raw data was processed following thematic analysis methods and then concluded into themes.

- *Usability* refers to the ease with which participants could interact with and manipulate the mini maps to achieve their goals. This theme captures both positive and negative experiences related to user interaction.
- *Navigation* includes participants' ability to locate themselves, others, and task-related objectives within the virtual environment. This theme reflects directional clarity, spatial orientation, and task efficiency.

- *Visibility* refers to the clarity and accessibility of the mini maps, including how well participants can see and interpret map elements.
- *Collaboration* refers to how mini maps supported or obstructed teamwork and communication between participants

The results presented below explain how potability, dimensionality and tangibility influenced each of the identified themes according to the qualitative data collected during the experiment. The purpose of the results is to see the impact of design features on user experience.

6.1 Impact of portability

Portable mini maps were the most flexible design, especially for enhancing usability and navigation. The adaptability of portable mini maps allowed participants to control the position of the map dynamically allowing them to adapt it to different situations. For example, participants mentioned that they could "bring the map into focus" and "reorient it manually with my hand", which made tasks smoother and more intuitive.

Usability was negatively influenced when participants needed to multitask. Some participants found that it was "confusing to use the left hand for the map while holding an object with the right". Other participants reported that "Toggling the map while performing tasks was not a pleasant experience." There was more friction when participants had to do navigation and object manipulation at the same time. In terms of navigation, portable mini maps were praised for helping one locate oneself or teammates. Participants said that being able to "describe directions as left or right to the other person" and "move quickly to the required areas" However, occasional issues with alignment and orientation were noted, particularly when participants needed to multitask while viewing the map.

Table 4 The process of the thematic analysis on the raw data collected from the 60 validated data collection session from industrial practitioners

Design feature	Matched themes	Selected raw data example
Portability (mini map A, B and E)	Usability	"It was easy to bring the map to my view, and I could reorient it with my hand."
	Navigation	"Being able to describe directions as left or right to the other person."
	Usability	"I had to close the tablet after grabbing to teleport – not easy to multitask."
2D (mini map A, C, D and E)	Visibility	"2D view feels easier to handle and see where my partner is."
	Navigation	"Only 2D can be hard to understand."
3D (mini map B)	Navigation	"The 3D map gave me a better perception of the layout and helped me orient faster."
	Visibility	"The map size was too big and obstructed my view, making it hard to multitask."
Tangibility (mini map A, B and D)	Usability	"I had to move physically closer to the map to see it, which took more effort."
	Navigation	"Finding my way around with this map was a bit harder to remember. Had to review my location and reorient myself to the map."
	Collaboration	"It was easy to show where my colleague was and discuss the next steps."

6.2 Impact of Dimensionality

Participants described 2D maps as "easier to handle" and noted that the 2D layout "made it easier to see where I and my partner were located." These strengths facilitate faster navigation in simpler tasks. However, limitations in spatial awareness were evident, with participants mentioning that the maps "lacked depth perception" and that it was "harder to understand complex layouts". A recurring suggestion was the inclusion of a "zoom option" to enhance usability.

On the other hand, 3D enhanced the navigation. 3D maps were praised for providing a "better perception of the layout" and "helping me orient myself faster." However, usability and visibility challenges arose due to their size and complexity. Participants reported that the maps were "too large and obstructed the view" and noted difficulties when toggling between map and task views. As one participant stated, "the map upon toggling was fixed on screen, and I had to physically move my head to see over it."

6.3 Impact of Tangibility

Participants improved navigation. For example, one participant described the maps as "good for referencing spatial locations," while another noted that they were able to "verify if I got where I intended to go." However, usability issues were frequently mentioned. Unlike portable maps, real-world maps were often stationary, requiring users to "physically step closer or teleport" to interact with them, which increased physical effort and interrupted task flow. This lack of adaptability limited their effectiveness for dynamic tasks. In terms of visibility, placement was another concern, with participants noting that "the map was too high up" or "out of reach" during critical moments.

7 Discussion

7.1 Universal Design principles across user groups

The mixed-design ANOVA results provide compelling evidence for identifying universal design principles that transcend the experience level of users in virtual navigation systems. Our analysis reveals that portability emerges as the most impactful design feature, with significant effects across nearly all mental and performance and spatial cognition experience metrics.

Portable minimaps significantly reduced mental demand ($p < 0.001$, $\eta^2 = 0.35$), physical demand ($p < 0.001$, $\eta^2 = 0.27$), temporal demand ($p = 0.01$, $\eta^2 = 0.26$), and frustration ($p < 0.001$, $\eta^2 = 0.30$), while simultaneously enhancing layout perception ($p < 0.001$, $\eta^2 = 0.43$), navigation ($p < 0.001$, $\eta^2 = 0.53$), and collaboration ($p < 0.001$,

$\eta^2 = 0.28$). The consistently large effect sizes ($\eta^2 > 0.14$) indicate that portability has substantial practical significance beyond statistical significance. This suggests that regardless of user expertise, portable mini maps reduce cognitive workload while enhancing spatial understanding-a universal design principle that benefits all users. Such outcomes align with mental workload theory, which suggests that minimizing extraneous mental demands allows users to allocate more resources toward effective navigation and decision-making (Sweller 1988, as well as avoid multitasking, especially interruptions, which can negatively impact performance due to higher mental workload (Mcmullan et al. 2021). The resulting improvements in layout perception, navigation, and collaboration under portable conditions indicate that fluid, user-controlled interfaces help users form clearer mental models of the environment, ultimately supporting better spatial understanding and task efficiency.

In contrast, dimensionality showed more selective effects, significantly impacting only layout perception ($p = 0.03$, $\eta^2 = 0.21$) and completion time ($p < 0.001$, $\eta^2 = 0.41$). Interestingly, non-dimensional (likely 2D) maps yielded worse layout perception, while 3D dimensional maps resulted in shorter completion times. This suggests that simplicity in representation may facilitate quicker comprehension of spatial layouts, though this benefit appears more context-dependent than portability. This observation contradicts with previous research that associated complex map features, such as 3D elements, with increased mental workload (Oulasvirta et al. 2009). Notably, 2D configurations did not consistently outperform their 3D counterparts, which is unexpected due to the initial assumption that a simpler design inherently reduces mental workload.

Tangibility demonstrated no significant main effects on any measure, suggesting it may be the least critical design feature among those tested. These finding challenges assumptions that tangible elements necessarily enhance navigation in VR environments.

7.2 User group differences and design implications

Our results revealed substantial differences between students and industrial practitioners across several metrics. Industrial practitioners consistently reported lower mental demand than students across all design features (all $p < 0.05$), with particularly pronounced differences in effort ratings (all $p < 0.001$, $\eta2 = 0.56$–0.65). This indicates that expertise significantly reduces perceived cognitive workload regardless of interface design-an important consideration when designing for mixed-expertise user populations.

This finding prompts a nuanced discussion regarding the interaction between domain expertise and interface design quality. Our results indicate that industrial practitioners, with their specialized knowledge, can effectively compensate for

suboptimal interface designs, even as portability consistently emerged as the most beneficial design feature for reducing mental workload across all participants. However, while students demonstrated positive responses to portable mini maps, their patterns of interaction were less pronounced than those of experts.

This observation presents an important consideration for VR interface design: experts may perform adequately even with less-than-optimal interfaces due to their domain knowledge, while novices may not fully benefit from isolated design improvements. Rather than suggesting that a single design feature can universally address usability challenges, our findings indicate that comprehensive interface design strategies may be particularly critical for novice users, who cannot rely on expertise to overcome interface limitations. This highlights the importance of considering user expertise levels when prioritizing design features in VR navigation systems.

However, despite these group differences, both students and practitioners showed similar patterns of response to the portable feature, underscoring its universal benefit. The absence of significant interaction effects between portability and user groups for many metrics (like navigation and layout perception) further supports the conclusion that portable design benefits transcend expertise levels.

7.3 Academic contributions—pattern recognition in VR during navigation

Through experimental implementation, our study expands the theoretical understanding of mental workload in VR by pinpointing portability as the primary driver to enhance user performance. We also provide empirical evidence that user-controlled interfaces enhance pattern recognition and spatial cognition, enabling users to intuitively process environmental layouts. This aligns with dual-process theories of cognition, where streamlined information flow—from encoding to decision-making—bolsters efficiency (Kahneman 2011). Different from earlier research that focuses solely on visual complexity, our findings highlight the value of minimizing extraneous mental workload through portable interfaces, offering a new opportunity for the study of cognitive ergonomics in VR.

From a methodological standpoint, our approach of combining NASA-TLX assessments (Hart & Staveland 1988), with prototype-based experiments provides a robust blueprint for refining theoretical frameworks in future industrial VR interface design, which can isolate the effects of specific design elements. Future investigation could include potential age- or gender-related disparities or examine the adoption of advanced input modalities—such as hand tracking, for more natural user interactions.

7.4 Practical Implications

From a behavioral design perspective, our results demonstrate that portability in mini map designs is the primary factor in reducing cognitive workload, which aligns with established strategies to combat decision fatigue in digital interfaces (Fogg 2009). The significantly lower mental demand, physical demand, and frustration scores for portable designs validate approaches that prioritize user control and accessibility. Based on our empirical findings, we propose several practical implications for universal design:

Prioritizing Spatial Control and Flexibility: The strong performance of portable mini maps across both user groups suggests that allowing users to reposition interface elements significantly reduces cognitive load. This aligns with Norman's (1988) principles that emphasize user control and freedom. Designers should prioritize interactive positioning capabilities in VR navigation tools, particularly in complex environments like factory layouts where spatial orientation is critical.

Optimizing Representational Fidelity: Our findings that 3D maps (not 2D) improved layout perception (p = 0.03, $\eta^2 = 0.21$) and reduced completion time (p < 0.001, $\eta^2 = 0.41$) challenge assumptions about simplicity always being preferable. This suggests that appropriate contextual representation that matches the task environment may be more important than minimizing visual complexity. Designers should consider matching representational fidelity to the cognitive requirements of specific tasks.

Addressing Expertise Differences: The significant differences between students and industrial practitioners across several metrics highlight the importance of accommodating varying levels of domain knowledge. While industrial practitioners consistently reported lower mental demand than students, both groups benefited from portable designs, indicating that well-designed interfaces can benefit users regardless of expertise level. This supports Marcus's (2009) recommendations for adaptable interfaces that accommodate different user capabilities.

Implementing Iterative Testing with Diverse Users: Our mixed-design methodology demonstrated the value of testing with both novice and expert users to identify universal design principles. As seen in our results, features that significantly reduced workload for both groups (like portability) represent the most robust design choices. This validates the approach of continuous A/B testing with diverse user groups recommended by researchers in VR prototyping (Freina and Ott 2015).

In summary, our empirical results advance practical VR interface design by demonstrating that portable, contextually appropriate representations can significantly reduce

cognitive workload while enhancing spatial understanding and task performance. These findings provide concrete guidance for developing VR navigation tools that balance usability with task appropriateness across different user expertise levels.

7.5 Limitations

While these findings are robust, several limitations must be acknowledged. While our mixed-design ANOVA provides robust evidence for these conclusions, several limitations should be considered. The expertise discrepancy between students and industrial practitioners introduces a potential confound that future studies should address through more controlled expertise matching. Additionally, the differential exposure to mini maps (three for students, five for practitioners) may have influenced results, though our analytical approach was designed to mitigate this concern. Gender diversity among industry participants was limited, potentially affecting the generalizability of the results. Although pilot tests did not show clear gender differences, a more balanced sample might reveal subtle variations. Age diversity was also not fully explored, and reliance on self-reported NASA-TLX data and uneven distribution of design features may limit the comprehensiveness of the study. A more controlled experimental setup, integrating additional variables and ensuring balanced prototype distributions, would strengthen future investigations.

Another set of limitations could originate from the design and development of the mini maps themselves. Design parameters not yet discussed in this paper could have had potential effect on the results or subjective evaluation of the mini maps by the participants. For instance, the size and dimensions of the different mini maps varied, which could have impacted how the participants perceived them. Furthermore, the positioning, look, size and transparency of the different mini maps could have an effect on the field of view (FOV), visibility or general liking by the participants. A methodological enhancement for future studies would be to implement a parametric evaluation approach, where participants directly rate the individual design features on standardized scales rather than evaluating complete mini map prototypes with predetermined feature combinations (e.g., "mini map A with portability level 1"). This approach would facilitate more precise isolation of design feature effects and potentially reveal interaction effects between specific parameters, thus providing more granular insights for interface design optimization in VR navigation systems.

7.6 Future Research

Future research should explore how these design principles transfer to different VR contexts beyond factory maintenance and whether the dominance of portability as a design feature persists across varied task domains and use cases. Longitudinal studies examining how these effects might change with increased user familiarity would also provide valuable insights for designing interfaces that evolve with user expertise for universal design principles.

8 Conclusion

This study systematically investigated how specific mini map design features-portability, dimensionality, and tangibility-influence mental workload and spatial cognition during collaborative navigation tasks in VR. By employing a mixed-design ANOVA and drawing on both quantitative (NASA-TLX, spatial cognition metrics) and qualitative (user interviews) data, we were able to assess the main and interaction effects of these features across student and industrial practitioner groups. The results clearly demonstrate that **portability** is the most impactful design feature, consistently reducing mental and physical workload while enhancing spatial understanding, navigation, and collaboration for both novice and expert users. Dimensionality (2D vs. 3D) showed more selective benefits, with 3D maps supporting better layout perception and faster task completion, suggesting that richer spatial representations can facilitate more efficient navigation in complex environments. Tangibility, by contrast, did not yield significant improvements in workload or spatial cognition, indicating that not all interactive features contribute equally to user experience or performance. Importantly, while industrial practitioners generally reported lower workloads and completed tasks more efficiently than students—reflecting the role of expertise groups benefited similarly from the introduction of portable mini maps. This suggests that well-designed interface features can provide universal benefits, regardless of user background.

In summary, our findings advance the understanding of cognitive ergonomics in VR interface design with an empirical study, emphasizing the value of portability and appropriate dimensionality for supporting effective navigation and collaboration for human-centric applications in the era of Industry 5.0. These insights offer practical guidance for designers and developers aiming to create intuitive, efficient, and user-centered VR systems for both industrial and educational applications. Future research should further explore the interplay of additional design parameters and user characteristics to refine universal design principles for immersive environments.

Data availability All data supporting the findings of this study are available upon request to the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

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