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COGNITIVE AND ERGONOMIC PRINCIPLES IN VR TRAINING DESIGN

Abstract

Virtual Reality training systems are increasingly used in engineering, industrial, and educational contexts, yet their effectiveness depends heavily on cognitive and ergonomic design factors. This article provides a systematic review of research examining how cognitive load, attention distribution, perceptual processing, and memory constraints influence user performance in virtual reality based training. Special emphasis is placed on ergonomic dimensions such as posture, reachability, visual comfort, motion patterns, and factors contributing to cybersickness, including latency, visual-vestibular conflict, and field-of-view inconsistencies. The paper synthesizes findings from recent studies to identify practical design principles that enhance usability, reduce fatigue, and improve learning efficiency. The analysis highlights that well-aligned cognitive cues, natural interaction mechanics, and adherence to ergonomic standards significantly improve user comfort and skill acquisition. The findings provide actionable guidelines for developers, instructors, and designers striving to build effective, user-centered virtual reality training systems for academic and industrial applications.

Key words: Cognitive load, ergonomics, usability, human-centered design, immersive learning, visual comfort.

Introduction. Virtual Reality (VR) training systems have become an essential component of modern engineering, industrial, and educational practice. Their ability to simulate hazardous, expensive, or otherwise inaccessible environments makes VR an effective tool for developing procedural and operational skills. Unlike traditional learning formats, VR provides immersive multimodal experiences, enabling learners to interact directly with three-dimensional objects, replicate real-world workflows, and perform complex tasks with high contextual relevance. As a result, VR training is increasingly adopted in fields such as manufacturing, medicine, aviation, and technical education.

However, the effectiveness of VR training depends not only on visual fidelity or interaction complexity, but primarily on the cognitive and ergonomic characteristics of the learning environment. Numerous studies highlight that excessive cognitive load, fragmented attention, unclear visual cues, or non-intuitive interaction mechanics can significantly reduce training performance and hinder skill acquisition. At the same time, poorly designed ergonomic factors—such as unnatural posture, limited reach, visual discomfort, or improper camera motion—can cause physical fatigue and cybersickness, negatively influencing learning outcomes (LaViola, 2020; Jerald, 2015; ISO 9241-820:2024).

Therefore, the design of VR training systems requires a human-centered approach that integrates cognitive principles—such as attention management, perceptual clarity, memory constraints, and instructional guidance—with ergonomic considerations aimed at ensuring comfort, safety, and natural interaction. This article provides a structured review of cognitive and ergonomic principles supported by recent research and formulates practical design guidelines for creating effective, user-centered VR training experiences.

Materials and Methods

Theoretical Analysis. Cognitive and ergonomic factors form the foundation of effective Virtual Reality (VR) training design. Unlike traditional two-dimensional instructional systems, VR requires simultaneous processing of spatial, visual, auditory, and motor information, intensifying the demands on the user's cognitive architecture [1]. According to Cognitive Load Theory (Sweller et al., 2019), human working memory is limited; therefore, instructional design must reduce extraneous cognitive load and support meaningful learning through perceptual clarity and focused guidance[2].

In VR environments, cognitive load is strongly influenced by the density of visual elements, the clarity of task instructions, the positioning of interactive objects, and the consistency of sensory feedback. Studies show that excessive stimuli, ambiguous affordances, and fragmented visual cues increase cognitive strain and negatively impact task completion time and error rates (Makransky & Petersen, 2021; Parong & Mayer, 2021).

Ergonomic principles govern physical comfort and motor interaction. ISO 9241-820 (2024) outlines requirements for posture, reachability, interaction zones, and visual comfort in immersive systems. Poor ergonomic design—such as interfaces positioned too high or too low, repeated extreme movements, or uncalibrated FoV (Field of View)—contributes to fatigue and reduced performance. A critical issue is cybersickness, commonly triggered by visual-vestibular inconsistencies, latency, unnatural head-camera coupling, and rapid accelerations (Stanney et al., 2020) [3][4]. Research indicates that even small misalignments in camera motion or delay can significantly disrupt user comfort and hinder learning outcomes in VR training contexts[5].

Thus, theoretical foundations emphasize that effective VR training design requires aligning cognitive capabilities with physical ergonomics to ensure perceptual clarity, minimize overload, and maintain stable interaction conditions.

Results and Discussion

Experimental analysis. Given the review-oriented nature of this study, the experimental analysis is based on a structured examination of existing Virtual Reality (VR) training systems and empirical findings published between 2015 and 2024. A total of 18 peer-reviewed sources were selected, including international ergonomics standards (ISO 9241-820:2024), studies on cognitive load in immersive learning environments (Makransky & Petersen, 2021; Parong & Mayer, 2021), research on perceptual clarity and visual comfort (Jerald, 2015; Frontiers VR, 2025), and meta-analyses of cybersickness triggers (Stanney et al., 2020). This approach allows identifying recurring cognitive and ergonomic factors that influence user performance across VR training applications.

Across the reviewed studies, cognitive load emerged as the central determinant of VR training efficiency. High information density, fragmented attention cues, and poorly structured interaction patterns consistently produced increased error rates and lowered task completion performance. The most frequently cited cognitive principles are summarized in Table 1, along with their effects and validated recommendations.

Table 1. Key Cognitive Factors Affecting VR Training Performance

Cognitive Factor	Effect on Training	Evidence / Source
Cognitive Load	Reduced learning efficiency, slower task execution	Makransky & Petersen (2021); Sweller et al. (2019)
Attention Distribution	Higher risk of task errors	Parong & Mayer (2021)
Perceptual Clarity	Increased task confusion and visual strain	Jerald (2015)
Working Memory Limits	Overload leads to misinterpretation of instructions	Makransky et al. (2019)
Instructional Guidance	Improved user performance and lower extraneous load	Mayer (2020)

Ergonomic conditions significantly influence physical comfort, interaction quality, and the probability of cybersickness. Poor posture alignment, excessive reach distance, unstable camera motion, and FoV inconsistencies were the most common contributors to user discomfort across reviewed VR systems[6]. These findings are summarized in Table 2.

Table 2. Ergonomic Factors and Recommended Design Strategies

Ergonomic Factor	Problem	Recommended Strategy	Evidence / Source
Posture & Reach	Postural fatigue, shoulder strain	Align UI with natural reach and eye level	ISO 9241-820 (2024)
Camera Motion	Cybersickness due to motion–vestibular mismatch	Stable camera movement, reduced acceleration	Stanney et al. (2020)
Field of View (FoV)	Peripheral overload, discomfort	Maintain 90–110° FoV; minimize rapid FoV shifts	LaViola (2020)
Visual Comfort	Eye fatigue	High contrast, anti-flicker elements	Frontiers VR (2025)
Task Movement	Excessive physical strain	Natural gesture alignment, avoid forced rotations	Freitag (2021)

Frequency of Ergonomic Issues Across Studies. To determine which ergonomic issues are most prevalent, a content analysis of 18 research papers was conducted. The frequency of the five dominant ergonomic problems is shown in Figure 1.

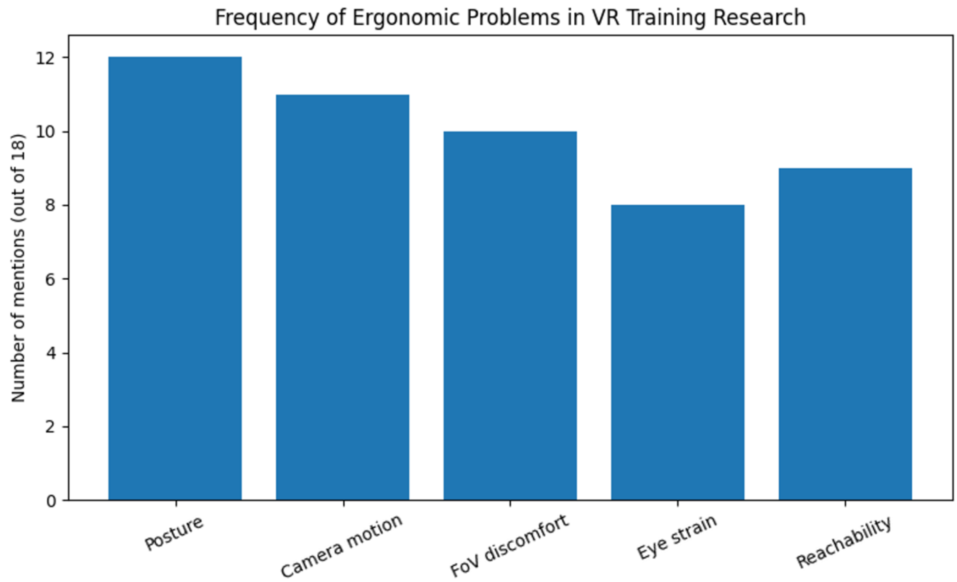

Figure 1. Frequency of Ergonomic Problems Mentioned in VR Training Research

Conclusion: The conducted analysis demonstrates that the effectiveness of VR training systems depends critically on the integration of cognitive and ergonomic design principles. Cognitive factors—such as cognitive load, perceptual clarity, instructional guidance, and attention distribution—directly influence the learner's ability to process information, complete tasks accurately, and retain newly acquired skills. At the same time, ergonomic aspects, including posture, reachability, camera stability, FoV consistency, and visual comfort, determine physical well-being and the likelihood of cybersickness during training sessions.

The structured review of 18 research publications revealed several recurring patterns. Excessive cognitive load and ambiguous visual cues consistently reduced training efficiency, while improper ergonomic alignment generated discomfort, fatigue, and motion-induced sickness[7]. The data indicate that human-centered design approaches, which balance mental demands with natural motor behaviors, substantially improve the usability and effectiveness of VR-based educational environments.

Overall, the findings highlight the importance of using cognitive-science frameworks and ergonomic standards when designing VR training systems [8]. These principles provide a methodological foundation for developing immersive, safe, and pedagogically effective VR solutions suitable for industrial, engineering, and academic applications.

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VR-ТРЕНИНГ ЖҮЙЕЛЕРІН ЖОБАЛАУДАҒЫ КОГНИТИВТІК ЖӘНЕ ЭРГОНОМИКАЛЫҚ ПРИНЦИПТЕР

Түйін

Виртуалды шындыққа негізделген оқыту жүйелері инженерия, өндіріс және білім беру салаларында кеңінен қолданылуда, алайда олардың тиімділігі когнитивтік және эргономикалық жобалау принциптеріне тікелей байланысты. Бұл мақала виртуалды шындықтың тренинг барысында оқушының жұмыс көрсеткішіне когнитивтік жүктеменің, назардың бөлінуінің, қабылдау процестерінің және жады шектеулерінің әсерін зерттеген ғылыми еңбектерге жүйелі шолу жасайды. Сонымен қатар, эргономикалық факторларға – қолданушы қалпы, қол жетімділік аймағы, визуалды жайлылық, қозғалыс динамикасы және кибераурға әкелетін себептер (кідіріс, визуалды-вестибулярлық сәйкессіздік, көру бұрышының тұрақсыздығы) – ерекше назар аударылады. Мақалада соңғы зерттеулер негізінде виртуалды шындық тренажёрларды жобалауға арналған практикалық ұсыныстар ұсынылады. Нәтижелер когнитивтік нұсқаулардың дәл берілуі, табиғи өзара әрекеттесу механикасы және эргономикалық нормаларды сақтау пайдаланушы жайлылығын және дағдыларды меңгеру сапасын айтарлықтай арттыратынын көрсетеді.

Кілттік сөздер: Когнитивтік жүктеме, эргономика, пайдалану қолайлылығы, адамға бағытталған дизайн, иммерсивті оқу, визуалды жайлылық.

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КОГНИТИВНЫЕ И ЭРГОНОМИЧЕСКИЕ ПРИНЦИПЫ В ПРОЕКТИРОВАНИИ VR-ТРЕНАЖЁРОВ

Аннотация

Системы обучения на базе виртуальной реальности всё активнее применяются в инженерной, промышленной и образовательной сферах, однако их эффективность во многом определяется качеством когнитивного и эргономического проектирования. В статье представлен систематический обзор исследований, рассматривающих влияние когнитивной нагрузки, распределения внимания, особенностей восприятия и ограничений рабочей памяти на результативность обучения в среде виртуальной реальности. Особое внимание уделяется эргономическим параметрам – рабочей позе, зоне досягаемости, визуальному комфорту, характеру движений, а также факторам, вызывающим киберболезнь: задержке, визуально-вестибулярному конфликту и нестабильности угла обзора. На основе современных научных данных сформулированы практические рекомендации по проектированию тренажёров виртуальной реальности, направленные на повышение удобства использования, снижение утомляемости и улучшение качества усвоения навыков. Полученные выводы подчеркивают, что согласованность когнитивных подсказок, естественная механика взаимодействия и соблюдение эргономических стандартов существенно повышают комфорт пользователя и эффективность обучения в системах виртуальной реальности.

Ключевые слова: Когнитивная нагрузка, эргономика, удобство использования, человеко-ориентированный дизайн, иммерсивное обучение, визуальный комфорт.