

Exploring Design-Relevant Insights From Existing Heuristic Studies for Virtual Object Design in Virtual Reality

Begum Tureyengil, Cigdem Kaya, and Ahmet Hamurcu

Istanbul Technical University, İstanbul, Turkey

ABSTRACT

This study examines heuristic evaluation research in virtual reality (VR) environments to explore its relevance for the design of three-dimensional virtual objects. Although heuristic evaluation is widely applied in interface and interaction design, existing frameworks largely address system-level usability rather than the spatial, embodied, and manipulation-oriented characteristics of virtual objects. Current heuristic sets do not sufficiently account for the complexities of object-level interaction in immersive environments, leaving a gap between evaluation practice and object-centered design guidance. Through a systematic review of 30 studies published over the past decade, the analysis interprets reported findings and design discussions to identify object-relevant patterns across heuristic-focused VR research. Rather than treating existing heuristic sets as fixed evaluation tools, the study reframes them as a source of design insight for virtual objects. The findings reveal five recurring design dimensions, namely spatial placement, interaction naturalness, feedback, affordances, and consistency, which current frameworks address only implicitly. By consolidating these dispersed insights, the study clarifies how existing heuristic research can inform virtual object design and establishes a conceptual foundation for future object-centered heuristic frameworks. For designers and researchers working in immersive environments, this work demonstrates that a meaningful body of object-relevant knowledge already exists within the heuristic literature and can be drawn upon before purpose built frameworks become available.

Keywords: Virtual reality, Heuristic evaluation, Virtual object design, Human-centered design

INTRODUCTION

Virtual reality (VR) technologies have rapidly expanded beyond entertainment and gaming to a wide range of fields, including education, healthcare, industrial simulation, collaborative workspaces, and digital twin environments. Immersive technologies are increasingly used in daily life and professional applications. This proliferation makes the quality of user interactions in these environments more critical and increases the requirements for the design of interactive components. In immersive environments, interaction occurs not through traditional graphical user interface components, but through three-dimensional objects placed in the

virtual environment. Users access tools, documents, artefacts, or spatial interfaces through manipulations such as holding, moving, rotating, or activating these objects. In this context, virtual objects function not only as represented elements but also as interface components that guide user actions and enable interaction. As Bowman et al. (2005) demonstrate through their treatment of 3D widgets, virtual tools, and manipulation techniques, virtual objects in immersive environments simultaneously serve representational and functional purposes, shaping how users perceive and perform tasks. In human–computer interaction (HCI) research, heuristic evaluation has long been recognized as a valuable formative evaluation method. Originally introduced as a cost-effective usability inspection method, heuristics provide evaluators with structured guidelines for identifying design problems early in the development process. Because heuristic evaluation can be conducted quickly by small groups of experts, it has become widely used in interface design and usability research (Nielsen and Molich, 1990; Nielsen, 1994).

However, the application of heuristic evaluation to immersive environments presents new challenges. Traditional heuristics were primarily developed for two-dimensional graphical interfaces, where interaction occurs through screens, menus, and pointer-based input devices. In contrast, VR environments rely on spatial interaction, embodied movement, and real-time feedback mechanisms that extend beyond the scope of traditional usability frameworks. These differences have motivated researchers to adapt existing heuristic models or propose new ones tailored to immersive technologies. Recent studies have introduced heuristic sets for various VR contexts such as educational environments, gaming systems, digital twin platforms, and metaverse applications. While these contributions demonstrate growing interest in heuristic evaluation for immersive environments, the literature remains fragmented and often domain-specific. More importantly, most existing heuristic studies focus on system usability, navigation design, or interface structures rather than on the design of virtual objects themselves. This represents a critical limitation because interaction in immersive environments frequently occurs through direct object manipulation. Virtual objects serve as primary interaction units, shaping how users navigate, perform tasks, and interpret system feedback. Despite this central role, object-level design considerations remain largely implicit in heuristic frameworks. Issues related to spatial placement, manipulation behavior, feedback communication, and affordances are often discussed in relation to system usability rather than as properties of virtual objects.

This study aims to address this gap by examining how existing heuristic-focused studies in VR can inform the design of virtual objects. Instead of evaluating heuristic sets as fixed frameworks, the study analyzes the findings and design discussions within these studies to identify patterns relevant to object-centered interaction. Through a systematic review of heuristic related VR research published over the past decade, the study aims to clarify how

heuristic based research can contribute to the design of three-dimensional virtual objects and highlight opportunities for developing future object-centered heuristic frameworks.

HEURISTIC EVALUATION IN IMMERSIVE ENVIRONMENTS

Heuristic evaluation is widely recognized as one of the most efficient formative evaluation methods in usability research (Nielsen and Molich, 1990; Nielsen, 1994). The method involves expert evaluators examining interactive systems according to a set of predefined usability principles. Because heuristic evaluation can reveal a large portion of usability issues with relatively small numbers of evaluators, it is frequently used during early design phases when iterative improvements are still feasible (Nielsen, 1994).

In traditional interface design, heuristic methods have been widely applied in web design, mobile applications, and software interfaces. However, immersive environments introduce characteristics that complicate the application of conventional heuristic models. Unlike screen-based systems, VR interactions involve spatial perception, body movement, and sensorimotor coordination. Users interact with virtual environments through head-mounted displays, motion controllers, and gesture-based input mechanisms. These interaction conditions introduce new usability challenges such as spatial disorientation, interaction ambiguity, motion sickness, and difficulty interpreting feedback. As a result, researchers have questioned whether classical heuristic frameworks can adequately capture the complexities of immersive interaction. In response, a number of researchers have proposed heuristic frameworks tailored to virtual and immersive environments, with contributions ranging from early VR interaction heuristics (Sutcliffe and Gault, 2004) to virtual world usability guidelines (Rusu et al., 2011), and VR-specific playability principles (Desurvire and Kreminski, 2018).

Some studies extend traditional usability heuristics by incorporating VR-specific criteria such as presence, gesture-based interaction, and natural movement (Laine and Suk, 2024). Other studies propose entirely new heuristic sets tailored to specific contexts such as metaverse user interfaces (Omar et al., 2024), wearable VR educational applications (Othman et al., 2025), and digital twin design (Kotecha and McAdams, 2023). Despite these efforts, the literature reveals significant fragmentation: many heuristic sets are developed for highly specific applications, limiting their transferability across different VR contexts. Furthermore, existing frameworks tend to evaluate interaction at the system or interface level, with limited attention to how individual objects within the virtual scene are designed and perceived. This gap points to the need for closer examination of what existing heuristic studies implicitly reveal about virtual object design.

METHODOLOGY

This study adopts a systematic literature review approach to investigate the role of heuristic evaluation in VR research and to explore its potential implications for virtual object design. The review was conducted using the

Web of Science database. The search process included combinations of the keywords “virtual reality,” “heuristics,” “design” as well as related terms such as “digital twin” and “metaverse.” The initial screening was performed by analyzing titles, abstracts, and keywords to identify potentially relevant publications. Subsequently, the full texts of the selected studies were examined to evaluate their methodological approaches, proposed heuristic sets, and design-related findings relevant to immersive virtual environments. The search focused on studies published within the past decade in order to capture recent developments in immersive technology. The initial search yielded 54 publications, which were screened based on titles and abstracts. After applying inclusion and exclusion criteria, 30 studies were selected for detailed analysis. Studies were included if they explicitly addressed heuristic evaluation methods within VR-related environments. Studies were excluded if they (1) focused primarily on engineering performance metrics rather than interaction or design quality, (2) did not address heuristic evaluation as a central methodological component, or (3) were domain-specific to technical systems with limited relevance to human-centered object interaction in immersive environments. These studies consisted of journal articles, conference papers, and review publications representing various application domains including interaction design, education, healthcare, gaming, and industrial simulation.

The analysis consisted of two stages. In the first stage, each study was examined in terms of its research focus, methodological approach, and application domain. In the second stage, the reported findings and design discussions within these studies were analyzed to identify design-relevant insights related to virtual object interaction. Rather than evaluating heuristic sets as fixed evaluation tools, the analysis aimed to interpret the design implications embedded within these studies. Particular attention was given to findings related to spatial interaction, object manipulation, feedback mechanisms, and interaction discoverability.

FINDINGS

Heuristic evaluation is widely used in various fields of virtual reality research. Interaction design and educational technology are the most frequently studied areas, followed by game environments and industrial applications. In these areas, heuristic evaluation has been approached in two main ways. Some studies focus on developing new heuristic frameworks adapted to specific immersive contexts, addressing VR-specific challenges such as spatial navigation, motion perception, and sense of presence (Sutcliffe and Gault, 2004; Desurvire and Kreminski, 2018; Omar et al., 2024; Laine and Suk, 2024). Others apply existing heuristic sets to evaluate specific virtual reality systems (Fontão et al., 2019; Paes and Irizarry, 2018). Such evaluations are mostly conducted on experimental prototypes or application-specific environments and aim to identify design-related problems. Despite the differences in research objectives, some recurring themes emerge in the literature. The first is interaction complexity. Since immersive interfaces

often rely on gesture-based or controller-based input methods, users can frequently experience confusion when interaction structures are overly complex or inconsistent (Kaur and Yammiyavar, 2017). Another important theme is spatial organization. Many studies highlight problems arising from the incorrect positioning of interactive elements in the virtual environment. Objects positioned outside the user's field of view or beyond their comfortable access zones can complicate the interaction process (Sutcliffe and Gault, 2004; Bierig and MacNamara, 2020). Feedback mechanisms also stand out as an important design element. Immediate visual, auditory, or tactile feedback helps users understand the consequences of their actions and more easily perceive system states (Fontão et al., 2019; Nebeling et al., 2020). While these findings are often considered within the scope of system-level evaluations, they offer important implications for the design of virtual objects.

Implications for Virtual Object Design in VR

When the findings of heuristic-focused VR studies are interpreted from a design perspective, they reveal several key considerations for the design of virtual objects in immersive environments. Although many heuristic frameworks were originally developed to evaluate system usability, their findings contain insights directly relevant to object-level interaction within virtual environments. One of the most prominent issues concerns spatial placement and accessibility. In immersive environments, objects are spatial entities within a three-dimensional space, and their position relative to the user significantly influences interaction quality. Studies have shown that objects placed outside the user's comfortable reach zone or in areas that compromise natural navigation can increase interaction effort and lead to task failures (Bierig and MacNamara, 2020; Sutcliffe and Gault, 2004). When virtual objects do not correspond to users' real-world expectations, interaction becomes unnatural and disrupts task performance. Ensuring objects remain visible, reachable, and spatially coherent is therefore a fundamental design requirement. A second consideration involves interaction naturalness. Immersive systems aim to replicate real-world interactions through embodied gestures such as grabbing, rotating, or manipulating objects. Heuristic frameworks emphasise that interaction should approach users' expectations of real-world behaviour and that objects should afford natural action without restricting physical movements (Sutcliffe and Gault, 2004). Empirical studies comparing 2D and 3D interface elements further suggest that spatially intuitive interfaces lead to greater user preference and task efficiency, though familiarity with existing conventions continues to influence perceived ease of use (Kaur and Yammiyavar, 2017). Designing objects that support intuitive manipulation through appropriate affordances, scale, and movement constraints can therefore enhance both usability and engagement. Another critical factor is feedback. In VR environments, users rely on visual, auditory, and haptic cues to interpret the consequences of their

actions. Playability evaluation studies have identified feedback as a primary heuristic category, noting that its absence constitutes a recurring usability problem across different game types and development stages (Fontão et al., 2019). Similarly, mixed reality evaluation frameworks emphasise the need for standardised heuristics and metrics, as their absence makes it difficult to identify usability issues systematically (Nebeling et al., 2020). Effective feedback contributes to building user confidence in the interaction system. A fourth consideration relates to affordances and discoverability. Virtual objects must communicate their potential interactions through visual or behavioural cues. When affordances are unclear, users struggle to identify how objects can be manipulated. Clear affordances allow users to infer interaction possibilities without explicit instructions, which is particularly important where traditional interface guidance is limited (Desurvire and Kreminski, 2018). Finally, behavioural consistency across objects plays a critical role in supporting user learning and interaction fluency. Consistent patterns allow users to develop reliable mental models, enabling them to transfer learned interactions to new situations and reducing cognitive effort (Nielsen, 1994). This principle has been confirmed in immersive VR environments for building design review, where consistency emerged as a key heuristic dimension influencing interaction performance (Paes and Irizarry, 2018).

DISCUSSION

The findings reveal a notable convergence across otherwise fragmented literature. Rather than being drawn from any single framework, recurring themes emerged across studies representing different VR contexts, application domains, and methodological approaches. These themes consistently pointed to five dimensions of object-level interaction: how objects are positioned in space, how naturally users can manipulate them, how clearly the system communicates the consequences of actions, how well objects signal their interactive possibilities, and how predictably they behave across different situations. Rather than reflecting domain-specific concerns, this convergence suggests that these dimensions address something more fundamental, namely the conditions under which object-level interaction in immersive environments becomes intuitive, reliable, and meaningful. Taken together, they offer a preliminary conceptual basis for an object-centered heuristic framework. This object-level perspective gains further significance when considered alongside the experiential dimensions of VR interaction. Mohammad and Pedersen (2022) identify five key qualities of VR learning experiences, namely embodiment, empathy, flow, drift, and sense of presence, and argue that general-purpose heuristics fail to capture these experiential qualities. The five dimensions identified in this study can be understood as the practical, object-level conditions that support them. For instance, spatial placement and interaction naturalness directly shape the sense of embodiment; clear affordances and consistent behavior contribute to flow by reducing cognitive interruption; and effective feedback sustains presence

by confirming the consequences of user actions. This relationship suggests that object-centered design principles are not merely usability concerns but are deeply connected to the quality of immersive experience.

Despite this potential, the literature reveals that current heuristic frameworks are ill-equipped to evaluate object-level interaction systematically. Guo et al. (2024) demonstrate that applying heuristic assessment to VR systems is practically difficult without a shared mental model among evaluators, particularly for object-based interactions that require precision, physics-based behavior, and real-time responsiveness. Significantly, some frameworks have begun to address this gap explicitly. Othman et al. (2025) propose four dedicated heuristics for object selection and manipulation, distinguishing between isomorphic and non-isomorphic techniques, marking one of the few instances in the literature where object-level interaction is treated as an independent design category rather than a subcategory of system usability. Similarly, Omar et al. (2024) identify a “world interaction” heuristic that directly addresses how objects should communicate their interactive possibilities to users. These contributions confirm that object-level interaction requires dedicated heuristic principles, and that the field is beginning to move in this direction, though without a unified framework. By synthesizing object-relevant insights dispersed across otherwise fragmented VR research, this study establishes a conceptual foundation on which future object-centered heuristic frameworks can be built. The five dimensions identified here, namely spatial placement, interaction naturalness, feedback, affordances, and consistency, represent recurring design concerns that current frameworks address only implicitly. Making these concerns explicit, and developing them into testable heuristic principles validated across different VR contexts and user groups, remains a meaningful direction for future research.

CONCLUSION

This study set out to examine whether existing heuristic research in VR environments contains insights relevant to virtual object design. The findings confirm that it does, though these insights remain dispersed and largely implicit across a fragmented literature. By identifying five recurring design dimensions, namely spatial placement, interaction naturalness, feedback, affordances, and consistency, the study makes these implicit concerns explicit and positions them as a conceptual foundation for future object-centered heuristic frameworks. For designers and researchers working in immersive environments, this means that a meaningful body of object-relevant knowledge already exists and can be drawn upon before purpose-built frameworks are available. The practical value lies in reframing existing heuristic literature not only as an evaluation tool, but as a source of design guidance for virtual objects. As immersive technologies continue to evolve, developing explicit, transferable, and object-centered heuristic principles will become increasingly important for supporting consistent and user-centered interaction design in virtual environments.

ACKNOWLEDGMENT

This paper is derived from the first author's ongoing Ph.D. research at Istanbul Technical University. This study was supported by the Istanbul Technical University Scientific Research Projects Unit (BAP) under the doctoral thesis project, Project Code MDK-2023-44736 (Project ID: 44736).

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