International Cartographic Association
Association Cartographique Internationale

Revisiting perceptual properties of visual variables in mixed reality

Irma Kveladze [a,*], Pyry Kettunen [b]

[a] *Department of Sustainability and Planning, Aalborg University (AAU) – ikv@plan.aau.dk,*
[b] *Finnish Geospatial Research Institute (FGI) in the National Land Survey of Finland (NLS) - pyry.kettunen@maanmittauslaitos.fi*

* Corresponding author

Keywords: visual variables, perceptual properties, cartographic design, mixed reality

Abstract:

Perceptual properties of visual variables serve as the foundation for traditional cartographic design principles (Bertin, 1983; Slocum et al., 2009) and play a crucial role in establishing hierarchies, differentiating symbols, and interpreting spatial relationships within map elements (MacEachren, 2004). These properties are essential for effectively communicating geographic knowledge and enhancing cognitive understanding of spatial information (Lochhead & Hedley, 2021). While their importance in 2D (Garlandini & Fabrikant, 2009) and conventional 3D cartography is established (Kveladze et al., 2019), there is a lack of knowledge on whether these same properties function similarly in Mixed Reality (MR) applications (Billinghurst et al., 2014; Çöltekin et al., 2020). As MR platforms blend digital and physical spaces, the traditional assumptions regarding symbol selection and placement in flat or screen-based representations may change. The interaction between real-world objects and virtual overlays introduces additional perceptual factors, such as dynamic lighting, occlusion, and depth distortion, which significantly influence how visual variables are perceived and interpreted within immersive environments (Kveladze et al., 2019; Sutcliffe et al., 2019; Zhang et al., 2023).

The primary aim of this research is to assess whether the perceptual properties that have consistently informed map design in 2D environments translate similarly for immersive environments. For instance, colour is essential for establishing figure-ground relationships, highlighting thematic elements, and differentiating between categories (Slocum et al., 2009). In an MR environment, real-world lighting can significantly affect the appearance of digital overlays, potentially diminishing or enhancing colour contrasts. Furthermore, although symbols may be clearly recognisable in 2D or standard 3D maps, their effectiveness in an MR context can be compromised. Changes in the user's viewpoint, partial obstructions by physical objects, and the influence of real-world textures can interfere with shape recognition that might otherwise be consistent (Billinghurst et al., 2014). Furthermore, the colour value is employed to indicate quantitative differences or elevation in 2D maps, while in MR, this variable interacts with ambient lighting and shadows, making it challenging to control or predict how users will interpret lighter or darker virtual elements when superimposed on different real-world surfaces.

It is well-established that depth perception in MR poses significant challenges that cannot be overlooked (Zhang et al., 2023). Traditional cartographic methods, such as perspective view, shading, and layering, are fundamentally designed for flat media or 3D representations, making them challenging for effectively addressing MR scenarios. In contrast, MR integrates both real and virtual elements, which can result in inconsistent depth signals for users (Çöltekin et al., 2020; Zhang et al., 2023). For instance, a virtual building layer may appear "behind" a physical landmark from some angles but "in front of" it from others, depending on slight variations in head position, display calibration, or environmental lighting. This partial misalignment can result in user confusion and compromise task performance, which eventually might lead to information miscommunication (Kveladze & Kettunen, 2024). Understanding how to optimise the perceptual properties of visual variables paired with depth cues remains an open research question for MR map applications. Table 1 below outlines the challenges related to perceptual consistency and underscores the necessity for empirical validation of design principles specific to MR, as we have hypothesised their anticipated effects on perceptual consistency.

According to the above-discussed challenges, we hypothesise, that although visual variables may retain their conceptual functions in MR, the degree to which they remain perceptually consistent may differ significantly. Certain variables, like texture or orientation, might be amplified in importance due to the interactive nature of MR, where users can walk around or rotate the maps in real time. On the other hand, variables such as value or shape might face increased ambiguity as real-world lighting conditions, reflections, and partial occlusions introduce confounding perceptual signals (Liu et al., 2022; Zhang et al., 2023). Moreover, we anticipate that conventional depth cues, such as perspective or layering, may

Abstracts of the International Cartographic Association, 10, 161, 2025
32nd International Cartographic Conference (ICC 2025), 17–22 August 2025, Vancouver, Canada.
https://doi.org/10.5194/ica-abs-10-161-2025

create ambiguous or misleading spatial relationships in MR environments, particularly when virtual elements misalign with real-world geometry from changing viewpoints. These hypotheses emphasise the need for empirical studies that measure perceptual properties based on user performance, spatial cognition, and user satisfaction when interacting with MR-based cartographic representations. Thus, to address this existing gap, our study proposes a systematic evaluation consisting of a controlled environment where users will complete map-based tasks using a combination of qualitative and quantitative assessment methods.

Table 1. An overall comparative analysis of visual variables in traditional 2D, 3D, and MR geovisualization applications. The table outlines the challenges unique to MR and identifies the visual variables that exhibit perceptual robustness versus those that are prone to breakdown in immersive dynamic spatial contexts, as hypothesised in this research based on their expected perceptual consistency.

Visual Variables	2D Cartography	3D Cartography	Mixed Reality (MR)	MR-Specific Challenges	Expected Perceptual Consistency in MR
Colour	Strong for differentiation and emphasis	Same as 2D with depth-enhanced shading	Highly variable, influenced by ambient light	Lighting and reflections affect perceived hue and contrast	Moderate — context-dependent
Shape	Clear symbol recognition	Perspective distortion can occur	Recognition disrupted by occlusion and viewpoint	Real-world textures and obstructions reduce clarity	Low — highly sensitive to spatial occlusion
Size	Encodes magnitude and importance well	Adds depth and scale cues	Distorted by depth misjudgement and scale shifts	Size perception varies with position/distance and display calibration	Moderate — affected by depth ambiguity
Value (Light/Dark)	Good for representing quantity and elevation	Enhanced via 3D shading	Altered by real-world lighting/shadows	Hard to control contrast due to ambient interference	Low — unstable under varying light
Texture	Effective for distinguishing regions	Often secondary, less exploited	May gain salience through realism and surface blending	May clash with physical textures or go unnoticed	Moderate — potentially amplified
Orientation	Useful for direction and movement	Preserved in 3D layouts	Enhances realism and interactivity	May cause confusion if rotation isn't intuitive	High — improves with interaction
Depth	Implied through vertical placement, visual hierarchy, transparency and shading	Explicit in 3D via perspective	Misalignment with physical world might lead to confusion	Real-virtual misalignment can distort spatial logic and undermine depth interpretation	Moderate — inconsistent or unstable *

* Based on observed depth misalignment in immersive MR tasks in Zhang et al. (2023).

The anticipated result of this research is a collection of empirically grounded design recommendations that will identify which visual variables function effectively in MR and those requiring adaptation to effectively address the complexities of blending real and virtual spaces. The experimental outcomes are expected to reveal significant variability in the perceptual consistency of visual variables when applied in MR environments compared to traditional 2D and 3D cartographic applications. While variables such as orientation may demonstrate enhanced salience due to the interactive and spatial nature of MR, others, like shape, value, and colour, are likely to show reduced reliability under conditions involving ambient lighting, occlusion, and depth ambiguity (Billinghurst et al., 2014; Lochhead & Hedley, 2021). Additionally, traditional depth cues such as visual hierarchy and perspective may lead to spatial misinterpretation due to misalignment between virtual and physical elements (Çöltekin et al., 2020; Zhang et al., 2023). These empirical insights will be grounded in user performance and spatial cognition to identify which visual variables remain robust in MR and which require adaptation. Through this effort, we aim to deepen our understanding of cartographic design principles for immersive environments and provide guidance to map makers and application developers on optimising immersive map interfaces (Spur et al., 2020). Ultimately, enhancing our comprehension of the performance of visual variables in MR applications not only facilitates improved usability and user engagement but also significantly supports critical decision-making across various domains, including navigation, disaster response, and beyond (Lochhead & Hedley, 2021; Zhang & Nakajima, 2022). In doing so, this study advances the integration of traditional cartographic design principles with MR systems requirements to foster more intuitive and effective mapping in increasingly hybrid physical-virtual environments.

https://doi.org/10.5194/ica-abs-10-161-2025

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Abstracts of the International Cartographic Association, 10, 161, 2025
32nd International Cartographic Conference (ICC 2025), 17–22 August 2025, Vancouver, Canada.
https://doi.org/10.5194/ica-abs-10-161-2025