Original scientific paper

Design recommendations and future prospects for text legibility in augmented reality

ABSTRACT

This paper provides a systematic review of the literature on text legibility in augmented reality (AR) using the PRISMA methodology, with an emphasis on head-mounted displays (HMD) and screen devices. Based on the literature review, we propose design recommendations for legibility in AR. The analysis was carried out using the 10 most important parameters: font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments. The analysis shows that billboard and outline styles and light fonts on a dark background ensure the most reliable legibility. For static information, world-anchoring is recommended, and for dynamic information, screen-anchoring is advised. Level-of-Detail (LOD) approaches are shown to reduce cognitive load. Specialized fonts (e.g. SharpView) and adaptive algorithms that adjust the contrast, size and position of text in real time are also examined. The results indicate a marked dominance of research on HMD devices, although screen AR has great practical importance and requires more research. Regarding other research directions, the review noted hybrid approaches (HMD + smartphone), projection AR, and hardware/software upgrades such as colorimetric compensation and text position stabilization. Research on text legibility in AR for 3D text, text segmentation, and dynamic real-world scenarios remains underdeveloped. Future advances in text legibility in AR are related to the integration of typographical, perceptual and technical solutions, and reporting harmonization.

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Introduction

The purpose of the written word is to convey information, and this is only made possible by legible letters. Legibility refers to the reader's ability to recognize individual letters and the word that certain letters make up, while readibility or reading comfort has different meanings for researchers, but most often refers to how easily the text is understood and how pleasant it is to read (Richardson, 2022; Mills & Weldon, 1987). This ability depends on various factors such as letter shape, size, word letter spacing, line spacing, contrast, and lighting.

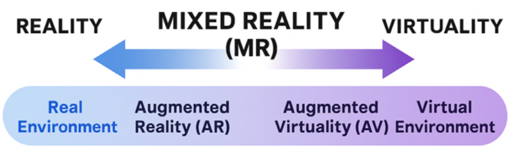
In this work, the focus in on legibility, but we also consider literature that involves readability in cases where the authors actually refer to legibility.

The advent of augmented reality (AR) in the early 2000s marked the beginning of a new type of technology, with its advantages and disadvantages. New research questions about text legibility were raised as soon as certain devices that enable AR became openly available. Augmented reality combines the real and virtual worlds by adding digital elements such as image, sound, video, and touch to the real environment in real time.

Unlike virtual reality (VR), which fully immerses the user in the virtual world, AR complements reality without complete replacement (Rampolla & Kipper, 2013). AR mainly uses head-mounted displays (HMDs) (such as smart glasses), but also smartphones and tablets to display information that integrates with the user's environment. The main challenge in an AR environment is to ensure the legibility of text despite changing conditions such as ambient light, complex backgrounds, and the user's distance from virtual elements.

In recent research, the term mixed reality (MR) is increasingly accepted as a more precise framework for describing digital systems that connect the real and virtual worlds. Although AR and MR are often used interchangeably, the term MR has a broader meaning that includes positioning virtual content in a space, interacting with the user in real-time, and adjusting the display according to the user's perspective.

The reality-virtuality taxonomy was introduced by Paul Milgram and his associates back in 1994 (Milgram & Kishino, 1994), and it was explained in detail by Dörner (Dörner et al., 2022). According to this approach, AR and augmented virtuality (AV) represent two extremes within a single continuum, while MR encompasses all forms in which virtual and real content mix and interact with each other, as shown in Figure 1. However, as the vast majority of related research uses the term AR in the context of MR, this one will also use the term AR, implying that AR actually encompasses the MR terminology.



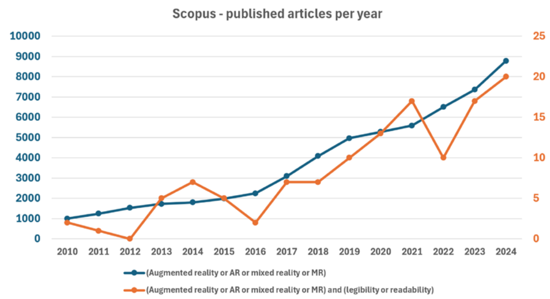
» **Figure 1:** *Mixed reality continuum, modified from Ko, Chang & Ji (2013)*

This paper includes the study of readability parameters for AR/MR when using mostly optically see-through (OST) HMD devices and screen devices. The paper does not consider readability in VR.

Based on the search of the Scopus database, Figure 2 shows how the number of research papers on AR and research papers on AR together with legibility have been increasing over the last 15 years. This clearly suggests that the field of AR and text legibility is still evolving and requires careful consideration.

The AR environment extends the methods of assessing the legibility of text used for text on paper and text on the screen. Large number of methods of assessing the legibility remains the same, such as measurements of the speed and accuracy of reading text and subjective assessments through a questionnaire (Richardson, 2022). However, some of the methods require adjustments. For example, the eye-tracking method is influenced by the depth factor in relation to the placement of the text. The eye dynamically adjusts to the difference in depth between the representation of text and objects in the scene, causing eye fatigue (Gabbard, Mehra & Swan, 2019). Also, the experimental manipulation of typographic elements must take into account the additional dimension of the display, which is reflected in the choice of text anchoring and the location of the text.

For this reason, new fonts and algorithms adapted to AR technologies are being tested, such as the SharpView font that optimizes legibility with unfocused text displays in AR systems (Arefin et al., 2024).



» **Figure 2:** *Search results of the Scopus database for scientific articles dealing with AR (blue) and AR with legibility or readability of text (orange)*

In this paper, we bring an overview of the literature on the topic of legibility of text in AR. This paper is an extension of the conference work (Jović, Mikota & Mandić, 2025). Instead of five, this paper examines ten legibility parameters using the PRISMA methodology for literature review (Page et al., 2021) and details design recommendations for HMDs and also for screen devices.

We note that other relevant review papers in this area are Erickson et al. (2020), Gattullo et al. (2022), and Cauz, Clarinval & Dumas (2024). In their work, Erickson et al. (2020) conducted a systematic review of visual perception in OST HMDs, analyzing 14 key papers with a focus on textual enhancements (billboard, outline, shadow), color and contrast, ambient lighting, color mixing, text location and size, and user demographics. Their paper provides an overview of research gaps and recommendations for the design of user interface (UI) elements on OST HMDs, but in the broader context of visual perception.

Our paper specializes in the legibility of the text and provides systematic design guidelines for legibility based on the PRISMA methodology. Gattullo et al. (2022) conducted a systematic review of visual assets in industrial AR applications for maintenance, installation, and staff training.

Their work classifies visual elements according to what they depict (text, photograph, video, sign, auxiliary model, drawing, technical drawing, product model), how they convey information (frame of reference, color coding, animation) and why they are used (locating, operating, checking, warning). Their work confirms the growth of AR adoption in industry, but Gattullo et al. (2022) primarily analyze the broader taxonomy of visual elements in industrial AR, while our work focuses on a detailed analysis of text legibility on HMDs and screen devices.

Cauz, Clarinval & Dumas (2024) conducted a comprehensive multivocal review of text legibility in AR and VR, including gray literature. In their study, they focused on seven legibility parameters: color and contrast, text drawing style, font type, font size, anchor, position, and text layout and segmentation. They offered two decision tree models for selecting the right text drawing style, text color, anchor and position for a text.

However, unlike them, our work excludes VR displays, focuses on HMD devices and screens, and brings a more systematic overview based on the PRISMA methodology with an analysis of ten key parameters of text legibility.

The contributions of this paper include:

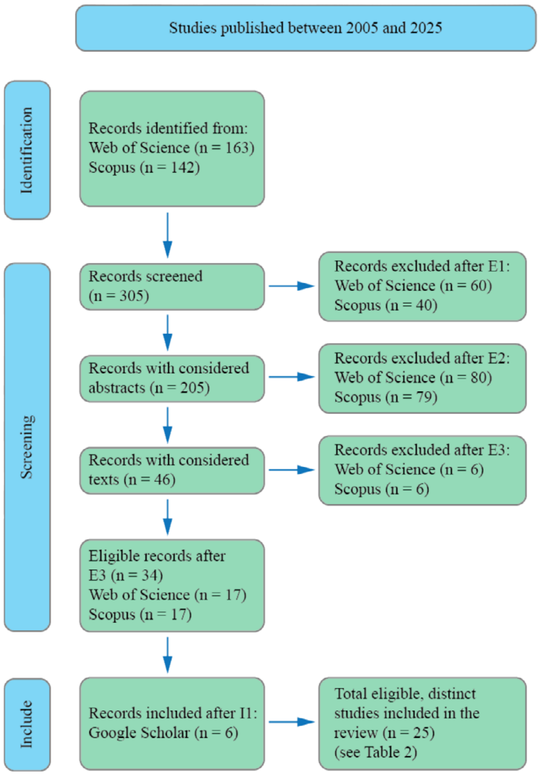
1. systematic review of the literature on text legiblity in AR based on the PRISMA methodology,
2. design recommendations for ten most commonly studied parameters of text legibility on HMDs and screen devices,
3. an overview of other observed research directions that are related to legibility.

Section 2 presents the PRISMA guidelines applied to the literature review on legibility in AR. Section 3 provides a literature review and highlights design recommendations for the studied legibility parameters. Section 4 discusses the results and provides an overview of other research directions. Section 5 presents the conclusions of the study.

Methodology

A review of the Web of Science (WoS) and Scopus databases was conducted systematically using the PRISMA methodology (Page et al., 2021). The review was conducted in three phases: Identification, Screening, and Include, as shown in Figure 3.

The criteria used to exclude and include articles are listed in Table 1.



» **Figure 3:** *PRISMA methodology for the systematic review of related work*

Table 1
Exclusion and inclusion criteria for the related work

No.	Exclusion and inclusion criteria
E1	Papers with unrelated research areas (e.g. medicine, chemistry, cartography, electrical engineering), retracted papers, papers dealing with AR hardware
E2	Papers not directly related to text legibility (including only text readability related papers), VR only papers, head-up display (HUD) only papers, papers in which text legibility is only a secondary topic, papers related to methods for contrast enhancements and occlusion reduction
E3	Papers with specific text legibility applications (e.g. non-Latin characters legibility, legibility on lunar surface), conference papers with the same topic later published in a scientific journal
I1	Papers cited in review papers from related work (see Section 1) that are indexed in Google Scholar, with the topic of text legibility and which may not be excluded based on E1, E2 or E3 criteria

At the beginning of the identification phase, the Query string "(augmented reality or AR or mixed reality or MR) and (legibility or readability)" was used in the WoS and Scopus databases.

The studies are limited to English and include original scientific and review articles. Studies ranging from 01/01/2005 to 01/09/2025 were included. 163 articles have been identified in the WoS database, and 142 in the Scopus database.

In the screening phase, in the first elimination step (E1), which included an overview of titles and keywords, articles were removed from those areas of research that are not related to the legibility of text in mixed reality, such as medicine and chemistry; articles that have been retracted and articles that deal exclusively with hardware topics in mixed reality. This eliminated 60 articles in WoS and 40 articles in Scopus.

Then, the summaries of the remaining abstracts were reviewed, and in the next step E2, those papers that were not directly related to legibility or included VR, HUD and other related but not direct topics for legibility in mixed reality were eliminated.

In the last step of exclusion (E3), the entire texts of the papers were considered and those papers that have a specific application for legibility and are therefore not widely applicable were removed. Also, the conference versions of the papers that were later published in the journal were removed.

In the last phase of inclusion, the review papers mentioned in Section 1 (Erickson et al., 2020; Gattullo et al., 2022; Cauz, Clarinval & Dumas, 2024) were additionally considered and the papers cited in them underwent the same review with the same elimination criteria (E1 – E3) and the final list of papers included those indexed in the Google Scholar database.

Since the Google Scholar database does not allow searching for multiple keywords with logical conditions as the WoS and Scopus databases allow, it was not possible to conduct the same detailed search for the entire Google Scholar database.

However, by considering the WoS and Scopus databases and additional consideration of the papers cited in the reviews, all studies relevant to this topic were taken into account.

The final list includes 25 studies, 15 of them common to WoS and Scopus, 2 different ones for these two databases WoS: Kruijff et al. (2019), Erickson et al. (2021); Scopus: Gabbard et al. (2007), Jankowski et al. (2010) and 6 studies from Google Scholar.

We note that all articles considered in the screening phase after the first elimination (E1) were considered for other research directions (Section 4), including the articles cited in review papers.

Literature review on augmented reality legibility

Introduction to the considered literature

The evolution of augmented reality text rendering shows that legibility is the result of the interaction of optics, environmental conditions, and typographic decisions. Systematic reviews and experimental work suggest that most research is still conducted under controlled, static conditions, although environmental dynamics (user movement, background and light changes) significantly alter perception (Cauz, Clarinval & Dumas, 2024). In newer approaches, adaptive algorithms and eye perspective control to maintain contrast and avoid occlusion are increasingly prominent (Emsenhuber et al., 2023). Since AR is becoming more and more present in various fields such as industry, education, medicine and entertainment (Mekni & Lemieux, 2014), research dealing with the legibility of a text and its accompanying concept of readability is becoming more common (Gattullo et al., 2022).

The ten most frequently investigated parameters of legibility according to literature, which we analyze in this work are: font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments. This review summarizes the consensus and divergence on these legibility dimensions and derives practical design guidelines.

In Table 2, we present 25 studies that were selected based on the PRISMA metodology. The field is dominated by HMD studies: 20 out of 25 (~80%) are focused on OST/VST HMD, while 5 out of 25 (~20%) are focused on screen. This imbalance is expected because AR-specific phenomena (e.g., additive color mixing in OST, vergence-accomodation (VA) conflict) require testing on HMD. However, given the prevalence of handheld/screen AR, it makes sense to encourage more systematic research on screen as well, especially in dynamic scenarios.

Table 2 (part 1)
Prevalence of HMD and screen methodologies in the included studies

HMD	Screen	Author
x		Cauz, Clarinval & Dumas (2024)
x		Arefin et al. (2024)
x		Emsenhuber et al. (2023)
x		Wysopal et al. (2023)
x		Erickson et al. (2021)
x		Falk et al. (2021)

Table 2 (part 2)

Prevalence of HMD and screen methodologies in the included studies

HMD	Screen	Author
	x	Cardenas et al. (2021)
x		Fukushima, Hamada & Hautasaari (2020)
x		Erickson et al. (2020)
	x	Sawyer et al. (2020)
x		Kruijff et al. (2019)
x		Kim et al. (2019)
	x	Sonderegger et al. (2019)
x		Gabbard, Mehra & Swan (2019)
x		Merino, Bergel & Nierstrasz (2018)
x		Manghisi et al. (2017)
x		Vairinhos, Almeida & Dias (2016)
x		Gattullo et al. (2015a)
x		Gattullo et al. (2015b)
x		Debernardis et al. (2014)
	x	Dao & Gabbard (2013)
x		Fiorentino et al. (2013)
	x	Jankowski et al. (2010)
x		Gabbard et al. (2007)
x		Gabbard, Swan & Hix (2006)

In the forthcoming subsection we present an overview of the research on legibility by the key parameters.

Overview of legibility research by parameters

The ten legibility parameters considered in this review represent recurring dimensions through which text perception in augmented reality has been empirically studied. Each parameter captures a specific aspect of how virtual text is rendered, perceived, and interpreted within real-world environments. In continuation, we first define the ten legibility parameters considered in this work.

Font type refers to the typographic design of letterforms, including serif and sans-serif distinctions as well as purpose-designed AR fonts. In AR contexts, font type primarily affects character recognizability under conditions of limited resolution, reduced contrast, and variable focus, rather than aesthetic preference alone. Text style describes the graphical treatment used to separate text from the background, such as plain text, billboard, outline, or drop shadow, as well as 2D versus 3D representations. This parameter is used for improving background interference and maintaining sufficient contrast in visually complex environments. Color and contrast address the relationship between text color and text background, including polarity (light-on-dark vs. dark-on-light) and color selection. In AR, this parameter is influenced by display technology (OST vs. VST) and ambient illumination, directly affecting visibility, visual fatigue, and reading accuracy. Font size defines the physical or angular dimensions of text as perceived by the user. In AR, font size interacts with viewing distance, field of view, and device resolution, and is often dynamically adjusted to preserve legibility across spatial contexts. Text anchoring specifies the spatial reference frame of text placement, such as world-anchored, screen-anchored, or body-anchored positioning. Anchoring influences reading stability, cognitive load, and naturalness of interaction, particularly during user movement.

Text segmentation and organization encompass line length, line spacing, hierarchical structuring, and progressive disclosure of information. These properties affect reading speed and cognitive effort and are especially relevant when presenting multi-line or task-related information in AR. Environmental illumination refers to the level and distribution of ambient light in the physical environment. Illumination affects perceived contrast, particularly in OST displays, where virtual content competes with real-world luminance. Background influence captures the visual complexity, texture, and color variability of real-world surfaces behind the text. Uncontrolled or highly textured backgrounds may degrade legibility. Perception depth relates to the spatial distance at which text is rendered relative to the user and surrounding objects. Depth differences between virtual text and real content can induce VA conflict, affecting visual comfort and reading performance. Text display in dynamic environments addresses changes in text presentation under conditions of user movement, background motion, or varying lighting.

An overview of research on the legibility of font types in augmented reality

The choice of typeface is one of the first typographic factors considered in the AR context. Early work focused on comparing serif and sans-serif typefaces, but the findings in AR suggest that the simplicity of form and the avoidance of overly elaborate details may be more crucial than the typeface itself, especially under conditions of variable focus and contrast. In addition, specialized AR fonts appear that target reading outside of optimal focus. Cardenas et al. (2021) showed that no significant difference in readability was found between Arial, Times New Roman, Georgia, and Verdana fonts in the older population. Cauz, Clarinval & Dumas (2024) point out that fonts with too much detail should be avoided and that there is no consensus about the superiority of serif or sans-serif; in practice, Arial (sans-serif) is often used as the standard. Arefin et al. (2024) developed a specialized SharpView font for out-of-focus reading, which shows 24–44% better sharpness results compared to Arial; the findings suggest the benefit of purpose-designed AR fonts, with the need for further empirical verification.

An overview of research on the text style legibility in augmented reality

The text display style (plain, billboard, outline, drop shadow; 2D or 3D) directly determines the visibility of letters on changing, often complex AR backgrounds. Most works record gains in legibility when the text is separated from the background by a billboard or outline/drop shadow, with caution due to potential occlusion and loss of context. In practice, the parameters of opaque (opaque vs. transparent), polarity (light on dark vs. dark on light) and adaptive approaches (e.g. LOD) are also examined, while 3D variants of text are under-researched.

Gabbard, Swan & Hix (2006) showed that the billboard performed best on different backgrounds compared to plain text, while Gabbard et al. (2007) showed that drop shadow and outline improve legibility and the billboard was not the most effective due to poor color contrast control. Jankowski et al. (2010) found that negative polarity speeds up reading. The best results were obtained for billboard, medium for anti-interference (contrast outline) and drop shadow, while the weakest results were obtained for plain text.

According to Fiorentino et al. (2013), a billboard is the best option for legibility (black text on a white background), but shows the problem of occlusion. In the context of this paper, plain text, outline, and a combination of outline and billboard were also tested. In a short review study, Dao & Gabbard (2013) found that a high-contrast billboard is most commonly used on handheld displays, whereas in some studies drop shadow is used for text emphasis. Debernardis et al. (2014) found that a billboard significantly outperforms plain text, and the recommendation is blue billboard and white text with good contrast (for OST and VST HMD devices). Gattullo et al. (2015b) showed that in OST at lighting that is ≤1,000 lux plain white text is the most legible on a dark background, while billboard is most legible on a light background. At 4,000 lux OST is unusable; for VST 1,000–4,000 lux black plain text on a light background is the most legible, optionally 1 px white outline may be used (the billboard is also good, but increases occlusion).

Vairinhos, Almeida & Dias (2016) indirectly established that 2D text is subjectively more legible than 3D (embossed, wireframe), using the Arial font. Research by Kruijff et al. (2019) showed that along with black text, blue billboard is most often preferred for OST and VST, while for VST, the next preferred billboard color is green. Sawyer et al. (2020) showed that on complex backgrounds, drop shadow gives the best results; outline is effective when the text is bold (tested on screen, transferable to AR). According to Erickson et al. (2020), a billboard generally improves legibility, however, dynamically matching the billboard's colors to its surroundings can degrade reading performance.

Falk et al. (2021) found that an opaque (solid) billboard is more readable than a transparent one (50%). This was tested on OST HMD devices. Wysopal et al. (2023) used a LOD system that dynamically adjusts the display according to angle/distance. The billboard was dominantly used for the display of text. According to Cauz, Clarinval & Dumas (2024), billboard and outline most often increase legibility, while there is no need to combine them at the same time.

An overview of research on text color and contrast in augmented reality

Color and contrast determine the visibility and visual pleasingness of text in AR, especially due to the differences between OST and VST systems and changing lighting conditions. In the literature, the polarity of the display (the relationship between the color of the text and the background), the choice of text/background color and the effect of dark mode on sharpness and fatigue are most often examined. The findings suggest that brighter, cooler colors and high, stable contrast generally make it easier to read, but the optimal combinations depend on the type of device and lighting.

According to Gabbard, Swan & Hix (2006), green gives the best legibility results for plain text and they recommended avoiding red. Later, Gabbard et al. (2007) found that white, cyan, and green are more effective than red on OST HMDs. Similarly, Fiorentino et al. (2013) showed that, in industrial settings, plain red text is weaker than black, white and green and that the combination of white billboard and black text gives the best legibility results in industrial conditions. On handheld displays, according to Dao & Gabbard (2013), saturated, high-contrast colors (red, neon green, yellow) are recommended for plain text to make it stand out over unpredictable backgrounds. According to Debernardis et al. (2014), white text on a blue billboard, with good contrast, shows the best legibility in most situations. Similar results were obtained by Kim et al. (2019), who showed that dark background and light letters increase accuracy and reduce fatigue while reading. Erickson et al. (2020) found that using red color usually leads to unfavorable results on OST devices, while blue, green, and white are more reliable. They also showed that, for OST HMDs, negative contrast (dark background, light letters) is more favorable than the positive contrast. Likewise, Erickson et al. (2021) found that dark mode (dark background, light letters) on the HoloLens device increases sharpness and subjectively positive reading experience in low light (10–12 lux). Falk et al. (2021) showed that for OST HMDs, higher reading accuracy is given by the positive polarity of the text (blue text on a white background). Lastly, Cauz, Clarinval & Dumas (2024) found that bright colors (white, cyan, green) are more visible on the OST HMD devices, while black loses visibility. On the VST HMDs, high contrast helps, but too strong constrast can cause discomfort.

An overview of font size research in augmented reality

The font size directly determines the threshold for the visibility of letters in AR, especially when the contrast is low and/or read at greater distances. In the literature, the size is expressed in different units (mm/dmm, pt, visual angle, "Unity units"), and the common pattern is: larger font = better legibility, with the need for dynamic scaling according to distance and position of text in the field of view (central vs. peripheral).

Kruijff et al. (2019) found that larger fonts are preferable in the peripheral field of view, with size expressed in degrees of field of view (small/medium/large). Erickson et al. (2020) recommended using a sign height of approximately 2 inches (~50 mm) at a distance of about 2 m, with further increase for longer distances. Cardenas et al. (2021) reported that sizes of 8/10/12/14 pt on the screen significantly affected legibility, with 14 pt being the most preferred size. According to Falk et al. (2021), in a three-level test (20/30/40 "Unity" units) on the Vuzix device, the smallest size resulted in the fastest reading, while on the Moverio device, the size had no significant effect. Wysopal et al. (2023) showed that autoscaling (LOD) by distance increases legibility and reduces display clutter. According to Cauz, Clarinval & Dumas (2024), font size recommendations in AR are quite diverse, approximately 5–17 dmm for OST and 26–40 dmm for VST, and increasing the size is particularly helpful in low-contrast conditions.

An overview of research on text anchoring in augmented reality

Anchoring determines how the text is placed in relation to the user and the environment. It directly affects legibility, cognitive load, and naturalness of movement. In practice, anchoring is chosen according to the type of information and context: stable, "spatial" messages seek a peaceful reference in the world, while status/HUD information needs constant availability in the field of view.

Merino, Bergel & Nierstrasz (2018) warned that an insufficiently stabilized (non-fixed) world-anchored text can cause legibility problems, which highlights the importance of quality displacement tracking and filtering. Fukushima, Hamada & Hautasaari (2020) show that world-anchored text leads to faster reading, fewer errors and lower mental effort, while screen-anchored text increases cognitive load, slows down reading and promotes unnatural head posture. The research showed that participants walked more naturally when using world anchor. According to Cauz, Clarinval & Dumas (2024), a screen-anchored text is recommended for dynamic information, while a world-anchored text is more suitable for static content. When walking, a body-anchored text often proves to be more suitable than the screen-anchored text.

An overview of research on text segmentation and organization in augmented reality

Segmentation (line length) and typographic organization (line spacing, hierarchy of information) of text directly affect reading speed and cognitive load in AR. The general pattern from the literature suggests that shorter lines and clear inter-line spacing make it easier to track, while progressive content detection and depiction (Level-of-Detail, LOD) helps to dose information according to context – distance and task.

Sonderegger et al. (2019) showed that a modular (LOD) structure on screens increases the flexibility of access to information and makes it easier to focus attention on the requested data. According to Falk et al. (2021), a comparison of one, two, and three lines confirms that a multi-line layout (fewer words per line, up to three lines) is faster to read, while a single-line, long text display is the most inefficient one. Wysopal et al. (2023) showed that an LOD organization hides less important information over longer distances and displays details when the user is closer, thereby reducing clutter and maintaining legibility. According to Cauz, Clarinval & Dumas (2024), shorter lines of text and sufficient line spacing are recommended for better legibility, noting that these parameters are still poorly researched in AR and require additional validation.

An overview of research on the impact of environmental illumination on text legibility in augmented reality

Enivornmental illumination (lighting) directly determines the perceived contrast between text and background in AR and therefore affects OST and VST systems differently. On the OST, stronger ambient light easily "washes out" the virtual display, while VST uses auto exposure, and therefore maintains contrast at higher light levels better, but loses quality in the dark. The optimal combinations of color/polarity and text styles change with the lighting level.

Gabbard, Swan & Hix (2006) showed that in the range of ~2,000–20,000 lux, the differences in legibility between the text styles are small at lower lighting, but increase with the increase in light above ~3,000 lux where the billboard is best, followed by green plain text, while red plain text is the weakest. Gattullo et al. (2015b) stated that for OST HMDs up to ~1,000 lux it is better to use light text on a dark background or a billboard on a light background, while at ~4,000 lux the OST devices become practically unusable due to very high errors. For VST, the usability for text legibility is similar at ~1,000 and ~4,000 lux. Gattullo et al. (2015a) found that at ~400 lux (indoor conditions) white text on a blue billboard is the most legible, with the results for 1,000 and 4,000 lux coincide with the previous work. Kim et al. (2019) found that there is a strong influence of lighting on the OST HMDs and that there is a dark mode preference in darker conditions. Erickson et al. (2020) point out that on the OST HMDs, the increase in ambient lighting negatively affects legibility as it reduces the contrast between virtual elements and the physical background. According to Erickson et al. (2021), there are fewer errors at 200–270 lux than at 10–12 lux (narrowed pupil increases sharpness) and, in the dark, users prefer dark mode. Falk et al. (2021) showed that at approximately 500–1075 lux (office/cloudy day conditions), legibility is better than at 20–50 lux, with low light making it difficult to search for and read text. According to Cauz, Clarinval & Dumas (2024), on OST HMD devices, a brighter environment reduces legibility due to a drop in contrast, while on VST HMDs, automatic brightness adjustment helps maintain visibility, although low light degrades the display.

An overview of research on the influence of background on text legibility in augmented reality

The background in AR is often unpredictable and textured, which directly affects the perceived contrast and reading speed. The literature shows that monochrome/neutral surfaces and consistent lighting make it easier to read, while complex, colorful or wooded backgrounds reduce legibility. When the background cannot be controlled, background treatments (e.g., solid billboard) and filters to mitigate complexity (blur/scrim) are helpful.

Gabbard, Swan & Hix (2006) showed that in the best reading options (billboard, green plain text), the influence of the background is largely neutralized. Gabbard et al. (2007) stated that a brick background produces the most errors, while a monotonous bright building (consistent lighting) is the most favorable for text legibility. Jankowski et al. (2010) found no difference in legibility between a city video and a 3D video game, suggesting that the type of dynamic background is less important than text treatment or contrast. Fiorentino et al. (2013) pointed out that a neutral background (e.g., a motorblock) allows for the fastest processing of information. Debernardis et al. (2014) showed that, on OST HMD devices, a dark background improves legibility, while on VST HMDs, the contrast is crucial, not the color itself. Manghisi et al. (2017) confirmed that textured backgrounds reduce legibility even with optimal contrast. Sawyer et al. (2020) reported that Gaussian blur and scrim ≥ 30% have the best effect on complex backgrounds (findings from screen devices, transferable to AR). Falk et al. (2021) found that monochrome backgrounds have better legibility than abstract/colorful ones. Erickson et al. (2021) show that dark mode is preferred on both uniform and noisy, gray backgrounds, with noise further distorting the results, especially at higher illumination. According to Cauz, Clarinval & Dumas (2024), complex texture and low contrast impair legibility.

An overview of research on the impact of perception depth problems in augmented reality

Depth perception in AR is closely related to vergence–accommodation conflict: the user often reads virtual text at one optical depth while simultaneously observing physical objects at another. Such separation of focus can increase effort, slow down reading and increase eye fatigue. Therefore, the choice of text depth and display format (2D vs. 3D) have direct consequences on legibility and comfort.

Gabbard, Swan & Hix (2006) showed that varying text distances of 1, 2, and 4 m with uniform size did not significantly affect legibility, suggesting that moderate depth shifts alone may not degrade reading when the text size is adequately scaled. Vairinhos, Almeida & Dias (2016) found that distance estimation for 3D text (embossed/wireframe) is somewhat weaker than for 2D text, suggesting the advantage of 2D text display for precisely positioned information. Gabbard, Mehra & Swan (2019) showed that switching focus between real and AR-displayed text accelerates eye fatigue and degrades reading performance, especially when the differences in distance are greater. According to Cauz, Clarinval & Dumas (2024), vergence–accommodation conflict was highlighted as a central problem when reading in AR; the recommended text depths in the literature are in range of 1–10 m, with the optimal depth depending on the type of text and the usage scenario.

An overview of research on text display in dynamic augmented reality environments

In dynamic AR scenarios (user movement, background and lighting changes), legibility depends on the system's ability to adjust the display – color, contrast, size, and position of text in real time, and to avoid overlapping with the background. Although many studies were conducted in static conditions, the studies that address dynamics show clear guidelines for adaptive representation.

Gabbard et al. (2007) showed that a system that samples the background and selects the accent style (billboard/outline/drop shadow) can help, but it is necessary to ensure a sufficiently strong contrast between the text and the selected style to avoid color similarity and consequently poorer legibility. Kruijff et al. (2019) reported that for text highlighting, blinking is the most effective motion type for OST HMD displays, while circular motion is optimal in VST HMD environments. They also showed that background motion is not crucial for the choice of motion type. Emsenhuber et al. (2023) showed that eye-perspective view management (EPR-VM) outperforms static display and camera-guided repositioning (Baseline, HMD-VM) because it reduces overlap, double vision, and contrast loss, thereby improving legibility on OST HMDs.

Wysopal et al. (2023) introduced a LOD approach that dynamically doses/scales text according to distance and viewing angle, thereby maintaining legibility without display clutter. According to Cauz, Clarinval & Dumas (2024), real-time adjustment of color and contrast in relation to changing lighting and background is necessary, as many earlier studies were performed under static conditions, while dynamic scenarios significantly alter perception.

Recommendations for parameter design based on the considered literature

From the reviewed articles, design recommendations that ensure the best text legibility in AR can be established. Table 3 shows the recommendations, specifically divided depending on whether an HMD or a screen device is used.

Table 3 (part 1)
Design recommendations for font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments

Parameter	Design recommendations	Used literature
Font type	HMD: For optimal legibility, use simple sans-serif fonts (e.g., Arial, Verdana) and avoid decorative ones; when the text is out of focus, apply specialized AR fonts (e.g., SharpView). SCREEN: On classic screens, there is no clear advantage of serif or sans-serif; Arial is a safe standard, and Arial, Times New Roman, Georgia, and Verdana offer comparable legibility, including for older users.	Cardenas et al. (2021) Cauz, Clarinval & Dumas (2024) Arefin et al. (2024)
Text style	HMD: A billboard with an opaque background and high, stable contrast is recommended; the use of a single style (billboard or outline/drop shadow), without dynamic color matching is advisable. The LOD view helps to change the angle and distance. When occlusion is a problem, give preference to a drop shadow or a thin outline; prefer 2D text. Cool backgrounds (e.g., blue; in VST devices, green) are often preferred.	Gabbard, Swan & Hix (2006) Gabbard et al. (2007) Jankowski et al. (2010) Fiorentino et al. (2013) Dao & Gabbard (2013) Debernardis et al. (2014) Gattullo et al. (2015b) Vairinhos, Almeida & Dias (2016)

Table 3 (part 2)
Design recommendations for font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments

Parameter	Design recommendations	Used literature
Text style	SCREEN: On complex backgrounds, billboard gives the best results, and drop shadow can also be used. If you use an outline, it will give you better results with bold text. Plain text is the weakest option. Prefer negative polarity and high contrast.	Kruijff et al. (2019) Sawyer et al. (2020) Erickson et al. (2020) Falk et al. (2021) Wysopal et al. (2023) Cauz, Clarinval & Dumas (2024)
Color and contrast	HMD: High, stable contrast with opaque backgrounds is recommended; on OST devices, light colors (white, cyan, green) are more visible, black loses visibility or is reproduced as transparent, while red should be avoided. Blue color of the billboard and white text on a dark background proved to be the most effective. Dark mode (light letters on a dark background) increases sharpness and comfort, especially in low light. High contrast between text and background is key to improving legibility, but too strong contrast, especially with VST, can cause discomfort and increased effort. When changing focus frequently, it is useful to increase the edge contrast (SharpView-approach). SCREEN: High contrast is recommended with a slight preference for dark backgrounds and light text for higher accuracy and less fatigue. On unpredictable backgrounds, saturated, high-contrast colors (e.g., neon green, yellow, red) are used for highlighting plain text.	Gabbard, Swan & Hix (2006) Gabbard et al. (2007) Fiorentino et al. (2013) Dao & Gabbard (2013) Debernardis et al. (2014) Kim et al. (2019) Erickson et al. (2020) Erickson et al. (2021) Falk et al. (2021) Cauz, Clarinval & Dumas (2024)

Table 3 (part 3)

Design recommendations for font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments

Parameter	Design recommendations	Used literature
Font size	HMD: Font size has a significant impact on legibility, especially at low contrast, longer distances, and in peripheral vision. Units vary (pt, Unity units, dmm, arc minutes, mm); converted to pt typical recommendations are approximately ~14–48 pt (OST) and ~74–113 pt (VST), while at ~2 m it is about ~142 pt. Because of the differences between devices and scenes, automatic size adjustment (LOD) is the most efficient approach, with the validation of the minimum readable size per device. SCREEN: Larger size directly improves legibility. In the tested range, 14 pt was the most desirable. For the general and older population, ≥14 pt is recommended, and ≤10 pt should be avoided.	Kruijff et al. (2019) Erickson et al. (2020) Cardenas et al. (2021) Falk et al. (2021) Wysopal et al. (2023) Cauz, Clarinval & Dumas (2024)
Text anchoring	HMD: A world-anchored text for static information is recommended for better legibility and less mental effort. Screen-anchored text can be used for dynamic conditions. When walking, a body-anchored text is more suitable than a screen-anchored text. With world anchor, it is necessary to ensure the stable position of the text in space. SCREEN: A screen anchor with a consistent position of the elements is applied; anchoring to the environment or body is not applicable.	Merino, Bergel & Nierstrasz (2018) Fukushima, Hamada & Hautasaari (2020) Cauz, Clarinval & Dumas (2024)

Table 3 (part 4)

Design recommendations for font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments

Parameter	Design recommendations	Used literature
Text segmentation and organization	HMD: Short lines of text and clear line spacing improve legibility. Apply LOD (hide less important information at greater distances, gradually reveal details when approaching). The parameters of line spacing and length have so far been poorly researched. SCREEN: Organize content modularly/progressively (quick access to the required data), with short lines and adequate line spacing; multi-row blocks are typically read faster than a single long line.	Sonderegger et al. (2019) Falk et al. (2021) Wysopal et al. (2023) Cauz, Clarinval & Dumas (2024)
Environmental illumination	HMD: Legibility is most stable in medium to strong indoor lighting (~200–1,000 lux); very low light (≤50 lux) slows down reading, and very high (≥3,000–4,000 lux) degrades the OST due to a drop in contrast (often unusable). For OST, use high contrast/solid billboard and bright colors; In darker conditions, dark mode is preferred because it reduces visual fatigue. VST maintains legibility even at 1,000–4,000 lux (VST devices control contrast by automatically adjusting the brightness), but in low light the quality decreases. Too strong a contrast can cause discomfort. Controlled lighting in industrial settings (around 400 lux) ensures consistent results, while natural light can vary and affect legibility. The optimal solution is to maintain moderate lighting and use adaptive lighting systems, which is enabled by VST devices. SCREEN: There are no specific studies.	Gabbard, Swan & Hix (2006) Gattullo et al. (2015a) Gattullo et al. (2015b) Kim et al. (2019) Erickson et al. (2020) Erickson et al. (2021) Falk et al. (2021) Cauz, Clarinval & Dumas (2024)

Table 3 (part 5)
Design recommendations for font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments

Parameter	Design recommendations	Used literature
Back-ground influence	HMD: Prefer monochrome/neutral backgrounds with consistent lighting; textured and colorful backgrounds reduce legibility. On OST devices, a dark background is preferred and it is more important than the color of the background. When the background cannot be controlled, apply a solid billboard. SCREEN: Complex backgrounds make it difficult to read. Prefer uniform/neutral backgrounds. A possible solution is to use a background filter such as scrim or blur to neutralize the impact of background noise. There are no differences between the types of dynamic backgrounds if you use text that is clearly highlighted by one of the proven methods such as text on a billboard.	Gabbard, Swan & Hix (2006) Gabbard et al. (2007) Jankowski et al. (2010) Fiorentino et al. (2013) Debernardis et al. (2014) Manghisi et al. (2017) Sawyer et al. (2020) Erickson et al. (2021) Falk et al. (2021) Cauz, Clarinval & Dumas (2024)
Perception depth	HMD: Place the text at a depth close to the task in order to reduce effort and vergence–accommodation conflict. Avoid large depth jumps between text and real objects. In the practical range of ~1–10 m, choose the depth according to the scenario. The distance itself does not impair legibility if the size is proportionally scaled. Prefer 2D text for reading as 3D (embossed/wireframe) makes it difficult to estimate distances. SCREEN: Not applicable (no change in depth); focus should be on text size and contrast.	Gabbard, Swan & Hix (2006) Vairinhos, Almeida & Dias (2016) Gabbard, Mehra & Swan (2019) Cauz, Clarinval & Dumas (2024)

Table 3 (part 6)
Design recommendations for font type, text style, color and contrast, font size, text anchoring, text segmentation and organization, environmental illumination, background influence, perception depth, and text display in dynamic environments

Parameter	Design recommendations	Used literature
Text display in dynamic environments	HMD: The use of Eye-Perspective Repositioning (EPR-VM), which reduces overlap and contrast loss and improves legibility compared to static or camera-guided approaches, is recommended. To highlight content, text animations in sparing amounts are recommended, with blinking being more effective on OST and circular motion on VST. The movement of the background is not decisive. It is necessary to maintain a high contrast of text and background (text style) when applying billboard/outline/shadow. It is recommended to use systems that automatically change the display of text based on environmental conditions to reduce the cognitive effort of the user and improve perception. Algorithms for automatic, real-time, adjustment of color, contrast and text size would be ideal for maintaining good legibility during the user's movement or changing environment. SCREEN: There are no direct findings in the literature.	Gabbard et al. (2007) Kruijff et al. (2019) Emsenhuber et al. (2023) Wysopal et al. (2023) Cauz, Clarinval & Dumas (2024)

Discussion and other research directions

While the reviewed studies provide evidence for several legibility-enhancing strategies, the generalizability of these findings is constrained by variations in experimental conditions and hardware configurations. Namely, a large proportion of the literature is based on controlled laboratory settings with static users, stable illumination, and simplified backgrounds, which only partially reflect real-world AR usage scenarios. In this context, lighting conditions represent a major source of variability. Studies usually report results obtained under specific illuminance ranges (e.g., indoor office lighting), whereas outdoor or rapidly changing lighting environments can significantly alter contrast perception, particularly on OST HMDs. Consequently, recommendations related to color, polarity, and text style may not transfer uniformly across lighting contexts. Similarly, user movement is often limited or excluded in experimental designs, despite evidence that walking, head motion, and changing viewpoints introduce additional challenges such as reduced text stabilization and increased cognitive load.

Findings obtained from static reading studies may therefore overestimate legibility performance in dynamic environments. Optical hardware differences further limit cross-study comparability. Results obtained on specific OST or VST devices depend on factors such as display brightness, focal distance, field of view, resolution, and color reproduction. As a result, parameter thresholds (e.g., optimal font size, contrast levels, or depth placement) reported for one device cannot be assumed to generalize directly to others without validation.

Regarding the frequency of examined parameters in the considered literature, it is evident (see Table 3) that the most commonly examined parameters are the style of text display (billboard/outline/shadow), color and contrast, environmental illumination, and background influence. Somewhat less frequently, but consistently, font size and text display in dynamic environments are examined, while segmentation and organization of text, depth perception, text anchoring, and font type remain less covered. At the same time, research on HMD devices is considerably more prevalent than research on screen-based devices, largely because HMDs enable hands-free interaction. Nevertheless, persistent technological challenges affect current HMDs, including additive color mixing and limited contrast on OST displays, VA conflict with fixed-focus optics, sensitivity to ambient/environmental illumination (especially outdoors), and limited battery life with associated thermal constraints. These limitations partially explain why screen-based AR continues to offer advantages for detailed reading tasks, particularly in dynamic or visually demanding environments. Due to the scarcity of research, it is recommended to conduct more systematic studies on legibility in AR on screens, with more proposed harmonized metrics and field testing in dynamic scenarios.

In order to achieve improved legibility/readability, hybrid systems that combine HMD and screen devices have been explored. Recent research highlights the complementarity of these technologies: smartphones are better suited for detailed reading and precise 2D input, while HMDs provide spatial context and hands-free viewing. Bang & Woo (2023) showed that using a mobile phone as an auxiliary display alongside an HMD reduces subjective load and visual fatigue and improves perceived readability/comfort, although objective metrics may not always show significant progress. Grubert et al. (2024) examined text input via a smartphone keyboard with the display of information on different devices (smartphone, HUD, OST HMD), under static and dynamic conditions. Using only smartphones achieved the best performance and the lowest cognitive load when reading, while today's common OST HMD with a single focal plane reduces the speed (and in some places accuracy) of reading, especially during movement.

Bang et al. (2025) further demonstrated that the benefit of hybrid systems depends on the spatial proximity of its components. Specifically, when AR content and smartphone are located in the near zone, reading on the smartphone is more accurate and comfortable. As the distance increases, the cost of switching (looking, holding the device) decreases the benefit, so the phone needs to be switched to the input role or the AR text should be drawn closer. This indicates that there is the need for smart coordination based on the spatial relationships between the text and the device (HMD/phone) in order to choose the best reading device on which the text content will be displayed. From the perspective of foundational legibility parameters, the hybrid systems primarily address limitations related to contrast stability, background interference, and illumination sensitivity on OST HMDs by leaving detailed reading tasks to screens, where contrast, polarity, and background control are inherently more stable.

Beyond hybrid systems, projection-based AR, where text is projected directly onto a surface, has been investigated as an alternative display modality. Di Donato et al. (2015) showed that, under typical industrial settings (~500 lx, color controlled, different materials), projected text can achieve legibility comparable to monitors when surfaces with a pronounced 3D texture (grooves/relief) that deform the outlines of the letters are avoided. The research showed that wood and steel surfaces are efficient for text display, while blue text color is systematically weaker on all surfaces due to lower lighting in sum with the background. The practical implications of this work include the preference for uniform surfaces, the avoidance of blue color for key text, and software contrast enhancement (outline/billboard) when projection is unavoidable. Thus, projection AR can be seen as a modality that is particularly sensitive to environmental illumination and background influence, where surface material, texture, and color directly determine effective contrast and outline visibility, often necessitating stronger text styles. Future work should relate material selection, lighting and text style into predictive models of legibility and explore multimodal scenarios (HMD + projection) in dynamic environments.

In the context of mobile AR in interiors, 3D typography (using 3D instead of 2D text to display content) does not inherently guarantee improved legibility over 2D text. Instead, control of the thickness and depth (extrusion) of letters, local contrast (including "volumetric" shadows) and thoughtful positioning in the scene are crucial. Palm (2018) reported a slight preference for lighter text variants, but without the consistent advantage of color alone. In addition, thickness/depth and contrast have a greater impact on legibility than the choice of serif/sans-serif typeface. The recommendations of this study are: limit extrusion, explicitly test the contrast of edges/depths against the actual background, use sans-serif in visually rich environments, and plan the placement of text according to purpose instead of aesthetic preferences. Rather than introducing new legibility principles, 3D typography primarily amplifies existing challenges related to contrast control, background complexity, and depth perception. Further research is needed to determine the optimal parameters of legibility of 3D text in functional AR tasks and to propose consistent 3D text evaluation methods.

In addition to typographic guidelines, some of the newer works deal with hardware/software upgrades of devices that directly improve legibility in AR. Colorimetric compensation for OST HMDs using screen profiling can reduce additive color mixing errors and stabilize contrast, especially on darker backgrounds, although dark colors remain a challenge (Sridharan et al., 2013). Under dynamic conditions, when a person moves while wearing an OST HMD, the text on the display also moves. Text movement reduces its legibility, as it makes it impossible to use the vestibular-ocular reflex (VOR) of the eye. The use of VOR-inspired text stabilization during walking reduces text movement, increases forward gaze, and reduces discomfort, with the greatest gain over shorter distances (Koide, Kanari & Sato, 2022). On the optical hardware side, using an electrically operated attenuator to transmit light on liquid crystal (LC) lenses allows contrast to be maintained even under bright ambient light, thereby improving legibility, with current limitations such as chromatic aberration and small aperture (Wang et al., 2017).

At the level of available technology, Mekni & Lemieux (2014) emphasized the need for continued improvement of HMD devices, particularly toward multifocal, multiplanar and other solutions (Matsuda, Fix & Lanman, 2017) that address VA conflict. Until such display technologies mature, screen-based AR is likely to remain dominant for everyday reading tasks due to the prevalence, reliability and habitual use of mobile devices.

Lastly, we enumerate significant research gaps in underexplored areas. 1) 3D text legibility: There is a lack of systematic evaluation of 3D text legibility parameters in functional AR tasks and across different display technologies.

2) Screen-based and handheld AR: Environmental illumination and text display in dynamic environments are well studied in HMD-based AR but remain largely unexplored in screen-based AR, despite fundamental device differences. 3) Text segmentation and organization: There is a lack of systematic investigation into how segmentation parameters, such as line length, line spacing, hierarchical structuring, and LOD interact with dynamic viewing conditions, user movement, and background complexity. 4) Dynamic, real-world usage scenarios: Many findings are derived from laboratory-based, static conditions. Field studies that incorporate natural user movement, changing lighting, and complex backgrounds are still relatively rare, despite their importance for real-world AR applications. Addressing these gaps would enable more robust design guidelines and facilitate the transfer of research findings into practical systems across devices and application domains.

Conclusion

In this review, based on a systematic literature search following the PRISMA methodology, we have shown that legibility in AR is most reliably achieved by a combination of: 1) simple typographic solutions (opaque billboard or moderate outline, high and stable contrast, short lines in multiple rows, and LOD scaling), 2) controlled background and lighting conditions (neutral surfaces, dark-mode background in low-light conditions, avoidance of red text color on OST devices), and 3) proper anchoring (world anchor for static, screen anchor for dynamic information). The effects of font size and depth perception depend on the device, distance, and context of the task.

Therefore, the minimum readable settings must be validated on the target hardware and in the target environment. Legibility studies in AR were found to be strongly focused on HMDs (OST/VST), while screen/handheld-based usage scenarios were less frequently or only indirectly investigated. This review provides clear design recommendations for the 10 most commonly considered parameters of text legibility in AR, both for the use of HMDs and for screens.

When considering other directions of research, hybrid HMD+screen approaches have been shown to provide benefits primarily when AR content and smartphone are in the near zone, where reading on a screen device is preferred. When the distance between the devices increases, more advanced solutions are sought for the choice of devices for displaying or for adapting the proximity of text. Projection AR is confirmed as a viable alternative to screen and HMD on uniform surfaces under controlled conditions, while there is room for further research into 3D text and its legibility. Various hardware and software improvements for text display suggest that the way to improve legibility in AR lies in the integration of multiple aspects of the technology: simultaneous color compensation, display stabilization, and contrast/text size adjustments depending on conditions.

Future work should prioritize dynamic trials in real-world settings and systematically bridge findings across HMD, smartphone/screen, and projection-based AR, with stratified analyses by user populations and application domains. From a practical standpoint, given the diversity of devices and reporting practices observed in the literature, full methodological standardization is unlikely in the near term. Instead, a feasible step toward improved comparability would be the inclusion of supplementary conversion tables in legibility studies, translating key parameters, most notably font size, viewing distance, luminance, and visual angle, across commonly used units (e.g., pt, mm, dmm, degrees, arcminutes), based on explicitly reported experimental conditions.

In parallel, the community would benefit from greater transparency and partial alignment in the reporting of both objective and subjective legibility metrics, including illuminance (lux), luminance and contrast (Weber or Michelson), type size (dmm/mm/pt/angular size/arcmin), color difference (ΔE), and minimum reporting items such as device class (OST/VST), viewing distance, text depth and anchoring, and background characteristics.

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