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Measuring Visual Span in VR and Desktop Reading: A Comparative Study

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(a) Visual span profile **(b) Experimental apparatus** **(c) Trigram presentation in VR**

Figure 1: Study overview. (a) The trigram method used to derive a visual span profile. (b) Experimental setup for the desktop (Dell P2419H) and VR (Meta Quest 3 via Windows laptop) conditions. (c) Example stimulus presentation with letter positions specified in units of letter size relative to fixation.

Abstract

The visual span, defined as the number of letters that can be accurately recognized in a single eye fixation, is a fundamental sensory constraint on reading speed. While well-studied on desktops, visual span in virtual reality (VR) remains largely unexplored, despite the increasing use of text-heavy VR applications. This gap is critical, as VR's unique constraints (e.g., limited angular resolution, optical distortions, and vergence–accommodation conflict) may fundamentally restrict text intake. We present the first empirical study to directly measure visual span in VR using the trigram paradigm and compare it to a matched desktop baseline. Although the profile shape of the visual span was similar across conditions, its size was significantly reduced in VR, averaging 4.28 letters versus 10.72 on desktop (a ≈60% reduction). These findings reveal a fundamental limitation and lay the groundwork for designing more readable and efficient text experiences in immersive environments.

CCS Concepts

• **Human-centered computing → Laboratory experiments**; **Empirical studies in HCI**.

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Visual span, VR, Reading

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1 Introduction

As virtual reality (VR) evolves from a niche entertainment technology into a mainstream platform for productivity, education, and social interaction, users spend more time reading text in immersive environments. From reviewing documents and browsing the web in virtual offices to engaging with complex learning materials, the legibility and comfort of reading are becoming critical determinants of user experience and task performance.

In skilled adult readers, reading involves a series of continuous saccades along lines of text, interspersed with brief pauses known as fixations [29]. During each fixation, the eyes remain still enough to allow the acquisition of visual information, such as the details needed to recognize letters and words. The question of how much can be read in a single fixation has long intrigued researchers, leading to the concept of visual span, defined as "the number of horizontally arranged adjacent letters that can be accurately identified without moving the eyes" [20]. The visual span has a significant impact on reading performance, acting as a perceptual bottleneck that limits reading speed. Experimental evidence shows that increasing visual span by just one letter is associated with a 39% increase in reading speed [20]. Prior work has identified numerous factors influencing visual span, including typographic variables (e.g., letter contrast, print size [19], character spacing [33] and crowding [8]), reading proficiency [16] and ocular conditions.

While this body of research has established a robust understanding of visual span in traditional desktop displays, reading is no longer confined to static, planar environments. With the rapid advancement of extended reality (XR), immersive reading is increasingly common across professional, educational, and recreational contexts. These environments offer wide fields of view and support natural head and eye movements [1], creating both new opportunities and new perceptual challenges for reading in three-dimensional spaces. In particular, the design of readable and comfortable text layouts in VR requires careful consideration of how visual span constraints interact with font size, spacing, and visual fatigue, especially during prolonged or information-dense reading tasks [15, 23].

Yet, despite the growing adoption of VR, no studies have systematically examined the size or profile of the visual span in VR, nor how it compares to desktop reading under equivalent conditions.

To address this knowledge gap, this paper addresses the following research question: *How does the visual span measured in VR compare to that measured on a traditional desktop monitor when using an equivalent trigram paradigm?* To answer this question, we replicated Legge's classic trigram method in both environments under matched visual conditions. We then mapped out and compared the visual span profiles for both the VR and desktop displays. This work contributes (1) a setup for measuring visual span in VR and (2) the first empirical comparison of visual span profiles across VR and desktop displays. Understanding this fundamental difference is a prerequisite for creating readable and comfortable text layouts in immersive applications, directly impacting the design of virtual workspaces, educational systems, and accessible interfaces for users with visual impairments.

2 Related Works

Measuring the Visual Span. Several techniques have been proposed to measure visual span, the most widely used being the trigram method [21]. In this paradigm, participants identify strings of three unrelated letters presented briefly at varying positions to the left and right of a fixation point. Aggregated accuracy across trials yields a visual span profile, in which letter recognition accuracy is plotted as a function of eccentricity from fixation (see Figure 1(a)).

Other approaches include isolated-letter paradigms [9], longer random strings (e.g., pentagrams) [26], and gaze-contingent moving-window techniques for continuous reading [24]. Compared to these other methods, the trigram method isolates the sensory limitations most relevant to visual span by still capturing crowding effects while minimizing lexical influences, making it well suited for comparing perceptual constraints across display technologies.

Reading in Virtual Reality: HCI Perspectives. The HCI community has increasingly investigated reading in virtual reality from a perspective of interface design, offering valuable insights into how design choices influence reading performance, comfort and fatigue. These include presentation format (e.g., Rapid Serial Visual Presentation vs. paragraph layouts) [30], text anchoring (head-fixed vs. world-fixed) [30] and interface parameters such as text size, convergence distance, and viewing angle [3]. Beyond interface-level design, research has shown that reading in VR can enhance motivation, engagement, and learning outcomes in educational contexts [2, 12, 13], engaging even users who may otherwise be reluctant to participate in reading activities [32]. However, multiple studies report a performance cost for reading in VR: users typically read more slowly and process less information compared to desktop displays, even when comprehension remains similar [27, 28]. Text-intensive VR tasks are also associated with increased visual discomfort and fatigue [14]. Our work complements prior UX/UI-focused HCI research by measuring the underlying perceptual constraints that limit reading performance—the visual span.

Display Technology, Visual Acuity, and Accessibility in VR. Text legibility in VR is fundamentally constrained by the properties of near-eye display systems. Lynn et al. [22] show that pixels per degree (PPD) is the most relevant metric for evaluating display resolution in VR, as it captures the angular resolution available to the visual system. Current consumer VR headsets achieve approximately 25 PPD at the optical center of the lens, with resolution declining toward the periphery—well below the approximately 60 PPD achievable by the human visual system. Hoffman et al. [10] further demonstrate that content rendering resolution must be carefully matched to display capabilities, particularly for text, where insufficient angular resolution can significantly impair legibility.

In addition to hardware resolution limits, optical distortions and the vergence–accommodation conflict (VAC) [7, 11] are known to further degrade text perception in VR, particularly in peripheral vision. Importantly, reduced text legibility in VR also raises significant accessibility concerns. Dudley et al. [5] identify text readability as a major accessibility barrier in VR and AR systems, disproportionately affecting users with visual impairments or age-related vision changes. Thus, understanding the visual span in VR is not merely a technical issue but a foundational accessibility concern. Quantifying this perceptual bottleneck is a necessary step toward designing equitable and inclusive immersive interfaces.

3 Methods

Our protocol adapted the Trigram paradigm [21] to a VR setting while retaining a matched desktop display control.

Subjects. We recruited 13 participants aged 18–44, all with normal or corrected-to-normal vision. All subjects were students or researchers from Delft University of Technology. All participants had prior experience with VR headsets, with one participant reporting weekly usage.

Apparatus. As shown in Figure 1(b), the experiment consisted of two display conditions: VR and desktop display. Device specifications are provided in Table 1; detailed calculations are reported in Appendix A.1. It is important to note that the pixel distribution in Quest 3 is not uniform, as the density of pixels typically peaks at the optical center and gradually decreases towards the edges. The

	Desktop Monitor	VR Headset
Device	Dell P2419H	Meta Quest 3
Resolution	1920*1080	2064*2208(pixels/eye)
Pixel Layout	RGB	RGB
PPI (pixels/inch)	92	1218
PPD (pixels/degree)	25.3	25 (at peak)
Viewing Distance (cm)	40	40

Table 1: Desktop and VR Headset Features

Quest 3 achieves a peak PPD of 25 [1], with an estimated average of 21.95 PPD (horizontal) and 21 PPD (vertical) [2].

Stimuli. A trigram consists of three random lowercase letters taken from the *Courier Bold* typeface. Any trigrams that accidentally spelled meaningful words (e.g., "dog") were discarded to avoid lexical inference. We measured performance for trigrams on the horizontal line (0°) passing through the point of fixation. Along the line, positions were indicated by the number of letter slots left (negative values) or right (positive values) of the midline (see Figure 1(c)). On the desktop monitor, letters were rendered in a dark color at 23 pt against a white background (90% contrast), which corresponded to an x-height of 0.5° visual angle, matching the original study [21]. Likewise, in the VR headset, the trigram was rendered in a dark color on a virtual white screen positioned at a viewing distance of 40 cm. To keep other variables constant, the virtual screen matched the physical size of the desktop display, and the letters again subtended an x-height of 0.5° visual angle. The ambient environment inside the VR headset was set to a dark color to minimize distraction.

Pilot Test. Two rounds of pilot testing informed the final parameters. The first, with two participants, only covered the VR condition and, with 210 uninterrupted trials, revealed that continuous testing caused rapid fatigue and accuracy loss. The second pilot, with three participants across both conditions, showed that inserting two-minute breaks within blocks successfully mitigated fatigue and additionally informed the timing of trigram reporting and fixation placement.

Procedure. All participants first completed a brief demographic questionnaire, read an information sheet, and provided digital informed consent. They then performed the visual-span task twice, once in VR and once on a conventional 24-inch desktop monitor. Session order was counterbalanced to control for sequence effects.

Each session began with a familiarization phase, where participants read aloud the 26 letters of the alphabet, presented as trigrams, to ensure consistent pronunciation (e.g., distinguishing "m" from "n") and rehearse the left-to-right reporting. They also completed a few practice trials to learn the timing of the task. On every trial, a small red fixation dot appeared at screen center for 1.5 seconds; when the dot disappeared, a three-letter trigram flashed briefly (100 ms, no forward mask). Participants then had 3.5 seconds to report the letters aloud from left to right, or say "no"/"missed it" if nothing was perceived. Without interruption, the session moved into the formal test block. Each display condition contained 105 trials, comprising 5 repetitions of 21 slots. A two-minute break divided the block into two equal halves (53 trials / 52 trials), and a three-minute break separated the two display conditions. Figure 3 (Appendix A.2) illustrates the full experimental flow. Throughout testing, the experimenter transcribed every verbal report in real time, remaining blind to the stimulus presented on each trial; all sessions were audio-recorded for later verification. A letter was scored as correct only when both its identity and its position within the trigram matched the physical stimulus. The resulting proportion-correct data were subsequently fitted with split-Gaussian functions to derive visual-span profiles for each display environment.

Data Analysis. For each participant, letter recognition accuracy was calculated per slot position by comparing the participant's response to the presented trigram. To characterize the visual span profile, a split Gaussian function was fitted to the mean accuracy curve as a function of letter position [21]. Visual span width was defined as the total range of positions where the fitted curve exceeded 80% accuracy, following the criterion established by Legge et al. [21]. This procedure was applied at the group level for visualization (Figure 2) and separately for each participant to obtain individual width estimates for statistical comparison. We excluded from statistical analysis participants whose VR Gaussian peak did not exceed the 80% criterion, indicating that a valid visual span could not be measured in that condition. A paired-samples t-test was used to compare visual span width between the desktop and VR conditions. As a robustness check, we repeated the analysis conservatively coding these cases as 0-letter spans.

4 Results

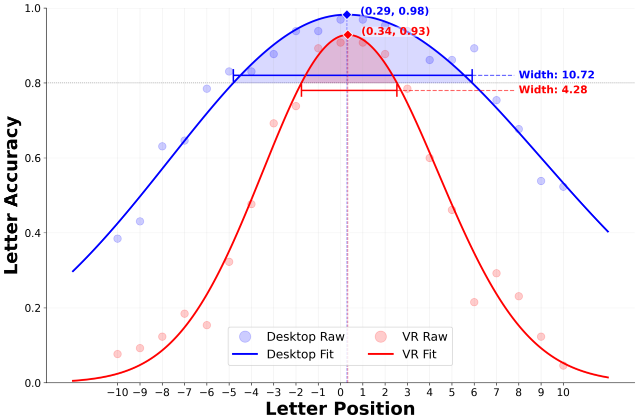

Figure 2: Visual span profiles for desktop (blue) and VR (red) conditions ($N = 13$). Points show mean letter-identification accuracy at each letter position, and solid lines show fitted curves. The exposure time was 100 ms.

Accuracy Profile. We fitted the letter recognition accuracy data (see Figure 4 in Appendix A.3) with split-Gaussian functions to

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[1] Data source: Meta Quest 3 Display Specs, available at https://www.meta.com/nl/en/quest/quest-3/

[2] Data source: Meta Quest 3 Display Specs on average PPD, available at https://vr-compare.com/headset/metaquest3/

derive visual-span profiles for each display environment. As shown in Figure 2, both the VR and desktop monitor conditions exhibited a characteristic "hill" shape, with accuracy peaking slightly to the right of the central fixation (Slot 0). The Gaussian center parameters indicated a minor rightward shift for both conditions ($CenterDesktop = 0.29$, $CenterVR = 0.34$). However, the peak amplitude was notably higher in the desktop condition (0.98) compared to VR (0.93), indicating that at the fovea (center of vision), recognition was slightly superior on the desktop monitor.

Visual Span Size. The primary metric for this study was the size of the visual span, defined as the width of the region where letter recognition accuracy exceeds 80%. Consistent with the profile shape, the visual span was visibly narrower in VR than on the desktop monitor. The estimated span width in VR was on average 4.28 letters (Left 2.08 + Right 2.20), whereas the span on the desktop monitor was more than double that size at 10.72 letters (Left 5.09 + Right 5.63).

Two participants were excluded from statistical analysis because their VR accuracy profiles did not exceed the 80% criterion at any position, meaning a valid visual span could not be derived. A paired-samples t-test revealed a significant difference in visual span width between the desktop and VR conditions ($N = 11$; desktop: $M = 11.84$, $SD = 2.90$; VR: $M = 4.98$, $SD = 1.39$; $t(10) = 9.70$, $p < 0.001$, $d = 2.92$). This difference remained significant when conservatively treating the two excluded VR cases as 0-letter spans ($N = 13$; desktop: $M = 11.49$, $SD = 2.98$; VR: $M = 4.21$, $SD = 2.32$; $t(12) = 8.54$, $p < 0.001$, $d = 2.37$), suggesting that the finding was robust to the exclusion criterion.

Individual participant profiles (see Appendix A.3) largely followed this aggregate trend, with the VR span consistently measuring narrower than the desktop span across subjects. Note that these individual-level means differ slightly from the group-level Gaussian estimates (4.28 and 10.72) reported above and in Figure 2, as the latter reflect a single fit to pooled data.

Asymmetry and Eccentricity. We observed a slight asymmetry in both viewing conditions. The right-side standard deviation (SD) was marginally larger than the left-side SD, indicating a broader recognition range in the right visual field—a known characteristic of left-to-right readers. Notably, the performance gap between the two conditions increased with eccentricity; while central accuracy was comparable, the decline in performance as distance from the fixation point increased was much steeper in VR than in the desktop condition.

5 Discussion

In the following, we interpret our findings in light of prior work on visual span, display technology, and immersive perception. We first discuss factors contributing to the narrower visual span observed in VR and then derive implications for the design of accessible VR reading interfaces.

5.1 Narrower Visual Span in VR

Our study compared visual span profiles between a VR headset and a traditional desktop monitor. While both environments exhibited similarly shaped profiles, visual span in VR declined more steeply with eccentricity, resulting in a substantially narrower span (4.28 letters) than on desktop displays (10.72 letters). The desktop result aligns with prior trigram-based findings [21], validating our replication and underscoring the robustness of the VR-specific reduction.

Several interacting factors likely contribute to this effect. Hardware limitations inherent to near-eye displays reduce peripheral resolution: although the Meta Quest 3 improves edge clarity over earlier devices, pixels per degree still decline toward the lens periphery, and distortion correction further degrades peripheral sharpness [17]. Because central PPD was matched between conditions, resolution alone cannot explain the lower peak accuracy in VR, indicating additional influences.

Physiological factors, particularly the vergence–accommodation conflict (VAC), likely further constrained peripheral recognition. The decoupling of vergence and accommodation in VR is known to impair visual performance and induce discomfort [7, 11]. Even with a constant virtual viewing distance, this conflict—combined with peripheral blur—may have reduced letter recognition at larger eccentricities. Environmental factors may also have contributed: the darker VR environment likely increased pupil dilation, reducing depth of field and retinal image quality [6]. Future work should better control luminance to isolate these effects. Additionally, individual differences in performance (see Appendix A.3) likely reflect participants' varying levels of prior VR experience and any pre-existing eye strain at the time of testing, both of which could influence visual comfort and letter recognition accuracy independently of the experimental conditions.

5.2 Design Implications

Our findings help explain slower reading speeds in VR compared to physical monitors [28]. Previous research indicates that each additional letter in the visual span increases reading speed by 39% [20]. Therefore, the approximately six-letter reduction we observed in VR predicts a severe decrease in reading speed of up to 86%. The reduced visual span acts as a perceptual bottleneck, requiring more frequent saccades and disproportionately disadvantaging users with reduced visual acuity or age-related vision changes. Addressing this constraint is therefore critical for both reading efficiency and accessibility in immersive environments. Our work has real-world implications for designing reading interfaces in VR. We propose three design strategies:

- **Center-Heavy Layouts:** Given the narrow visual span in VR (≈4 letters), text interfaces should avoid wide text blocks and place critical information near the center of the field of view.
- **Compensatory Typography:** Larger font sizes, increased letter spacing, and high contrast can help offset peripheral degradation in VR. Eccentricity-dependent typography, which increases text size or weight toward the periphery, may further preserve legibility across the visual field [4].
- **Support for Lexical Inference (Predictability):** Favoring predictable language and simple vocabulary can help compensate for restricted visual span by enabling longer saccades and improving reading speed, especially for users with limited visual capacity [18].

5.3 Limitations and Future Work

This study has several limitations that suggest directions for future research. First, we evaluated visual span using a single consumer headset (Meta Quest 3). Future work should examine devices with higher rendering resolutions and different optical designs to determine how improvements in peripheral sharpness affect visual span and reading performance [25].

Second, the slight rightward asymmetry observed in visual span likely reflects participants' left-to-right reading habits. Studies involving right-to-left readers (e.g., Arabic or Hebrew speakers) could test whether this asymmetry reverses, clarifying the role of reading direction in shaping visual span in VR. Third, while participants were instructed to maintain fixation on the central fixation dot during trials, actual gaze fixation was not verified. Future work could leverage gaze-tracking-enabled headsets to confirm fixation compliance. Finally, VR enables display configurations beyond flat, planar layouts. In our follow-up research, we intend to explore curved or spherical text presentations. Because display geometry influences search accuracy and reading speed [31], we hypothesize that a curved display maintaining a constant viewing distance (e.g., 40 cm) could reduce peripheral blur and vergence–accommodation conflict effects, potentially expanding the visual span toward desktop-like performance.

6 Conclusion

This work takes a first step toward understanding a fundamental perceptual constraint on reading in virtual reality by directly measuring the visual span in immersive displays. Using an adapted trigram paradigm, we compare visual span in VR with a matched desktop baseline. While span profiles showed similar shapes across environments, visual span in VR was significantly reduced, averaging 4.28 letters compared to 10.72 letters on a desktop display. This substantial reduction reveals a core sensory bottleneck that helps explain slower reading performance in VR. By quantifying this limitation, our findings position visual span as a critical constraint for the design of immersive reading interfaces and as an important accessibility concern. The results motivate concrete design strategies, including center-heavy layouts, compensatory typography, and support for lexical inference, and lay the groundwork for future work on adaptive or curved VR text layouts that better align immersive displays with human perceptual capabilities.

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A Appendix

A.1 Calculation of desktop PPD

1. Convert PPI to PPCM (Pixels Per Centimeter)

$$92\ \text{PPI} \div 2.54\ \text{cm/inch} \approx \mathbf{36.22}\ \text{pixels/cm}$$

2.Calculate the Physical Size of 1 Degree At a distance of 40 cm, use the formula: $\text{Width} = \text{Distance} \times \tan(1^\circ)$

$$40\ \text{cm} \times 0.01745 \approx \mathbf{0.698}\ \text{cm}$$

3.Calculate PPD Multiply the pixels-per-cm by the cm-per-degree.

$$36.22\ \text{px/cm} \times 0.698\ \text{cm/degree} \approx \mathbf{25.3}\ \text{PPD}$$

A.2 Procedure

The complete timeline of the experimental procedure, including the familiarization phase and formal test blocks, are illustrated in Figure 3.

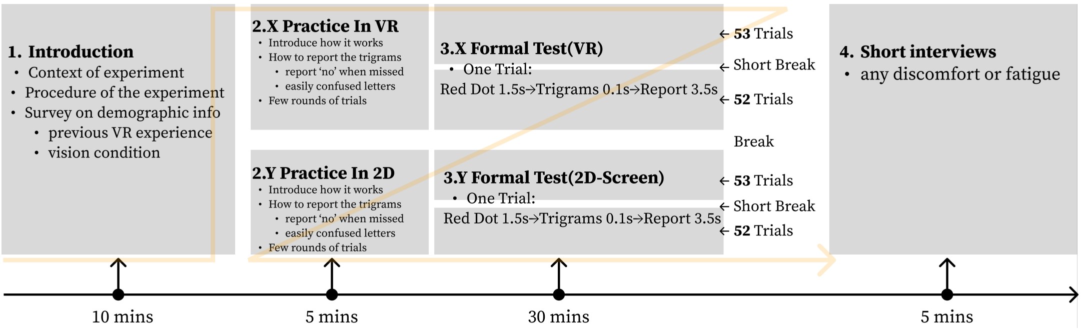

Figure 3: Flow diagram of the experimental procedure.

A.3 Raw Data

The individual visual span accuracy profiles for all 13 participants across both viewing conditions are presented in Figure 4.

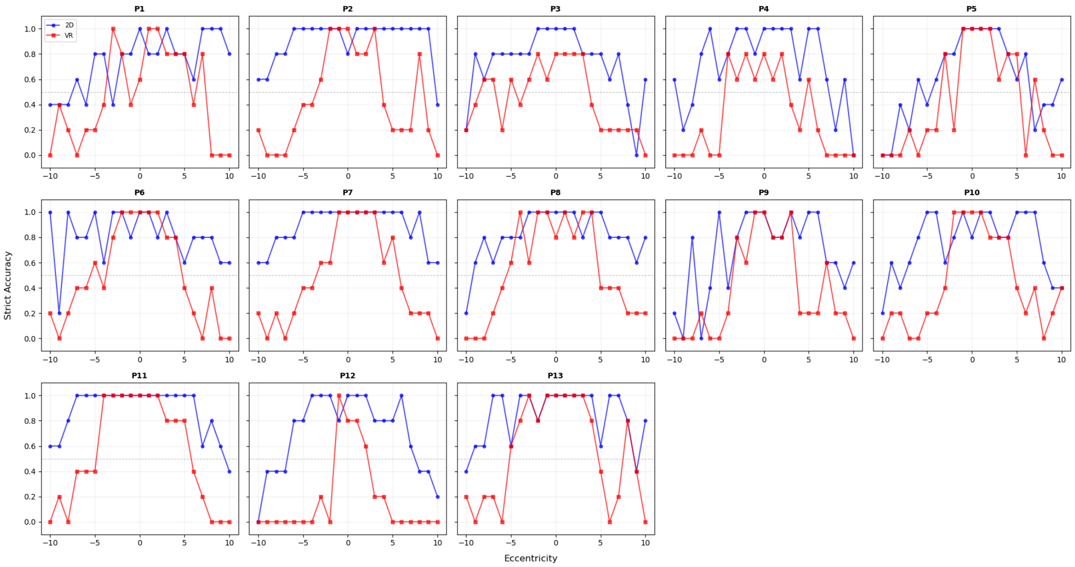

Figure 4: Raw data of $N = 13$ participants.