Flow and Long-Form Reading in Mixed Reality

Colin A. Brett
colin.brett@unb.ca
University of New Brunswick
Canada

Ernst Kruijff
ernst.kruijff@h-brs.de
Hochschule Bonn-Rhein-Sieg
Germany

André Hinkenjann
andre.hinkenjann@h-brs.de
Hochschule Bonn-Rhein-Sieg
Germany

Scott Bateman
scottb@unb.ca
University of New Brunswick
Canada

Abstract

When someone is in a state of *flow* while reading, they are totally immersed, losing track of the physical act of reading. Flow in reading is desirable because it is strongly associated with enjoyment and interest in the content being read. It is unclear, however, whether mixed reality devices—which can be heavy, uncomfortable, and lack display clarity—can support the flow experience as well as conventional reading technologies. In this work, we compare a virtual reality headset (VR HMD) and a see-through augmented reality headset (AR HMD) to a tablet (with an LCD screen) and an eReader (with an e-ink display) in a controlled reading study. Critically, we find that both the VR and AR HMDs better support readers' experience of flow than the eReader and LCD tablet in long-form texts. Our findings provide valuable new insights into the study and understanding of reading experiences in mixed reality.

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; *Interaction paradigms*; *Empirical studies in interaction design*; *HCI theory, concepts and models*.

Keywords

mixed reality, augmented reality, virtual reality, reading experience, flow

ACM Reference Format:

Colin A. Brett, Ernst Kruijff, André Hinkenjann, and Scott Bateman. 2018. Flow and Long-Form Reading in Mixed Reality. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation email (GI '26).* ACM, New York, NY, USA, 12 pages. https://doi.org/XXXXXXX.XXXXXXX

GI '26, WATERLOO, ON

ACM ISBN 978-1-4503-XXXX-X/2018/06
https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

Long-form reading—broadly defined as reading content such as books or articles exceeding one thousand words [2, 53]—demands sustained attention and focus. Through such engagement, reading can induce a state of *flow*. Flow, as described by Csikszentmihalyi [14], is a state of deep psychological immersion in an activity, characterized by intense focus, diminished self-awareness, and an altered perception of time [15]. In reading, flow has been associated with deep narrative immersion, increased enjoyment, and improved comprehension [16]. Supporting flow during long-form reading is therefore a meaningful design goal.

As mixed reality (MR) headsets gain traction for both productivity and entertainment, there is increasing interest in supporting extended reading experiences within these devices. However, prior research on reading in MR has largely focused on short-form content, augmented text, or task-oriented comprehension scenarios. As a result, the experience of prolonged, uninterrupted reading in MR—and its relationship to flow—remains underexplored [4, 22, 49].

In this work, we address this gap through a comparative study of long-form reading in mixed reality, evaluated alongside baseline devices commonly used for digital reading. We developed a cross-platform reading application that enabled participants to read the same continuous narrative text across four devices: an e-ink **eReader**, a high-resolution **LCD** tablet, a fully immersive virtual reality headset (**VR HMD**), and a see-through augmented reality headset (**AR HMD**). Using a within-subjects design, participants read a novel continuously under each condition. We measured reading performance, cognitive workload, subjective impressions, and flow. By holding content, text parameters, and interface constant while varying only the device, our study isolates how device characteristics shape extended reading experiences.

Our results show that both VR and AR head-mounted displays elicit significantly higher experiences of flow than handheld devices. We also find that the AR HMD and eReader impose significantly lower cognitive workload (NASA-TLX) than the VR HMD and LCD tablet, and that the LCD tablet produces significantly more reading errors than the AR HMD. Together, these findings highlight both the promise and limitations of MR for long-form reading, clarify its viability for

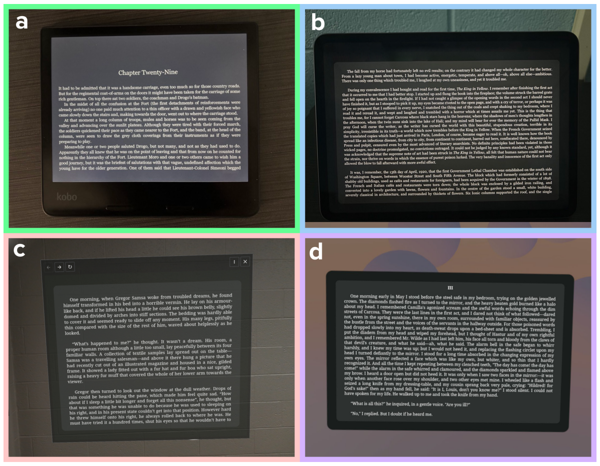


Figure 1: The reading view of each device condition: a) eReader b) LCD tablet c) MR HMD d) VR HMD.

sustained engagement, and inform the design of future spatial reading systems. This work makes three main contributions:

- Empirical evidence that MR headsets can support flow during long-form reading.
- Identification of design trade-offs and usability considerations for MR reading systems.
- A descriptive framework based on form factor and display technology to guide future study of MR reading devices.

2 Related Work

2.1 Digital Reading

Reading has long been central to our interactions with digital systems. From early terminal-based character-cell displays to the contemporary high-resolution screens of smartphones, tablets, and dedicated e-readers, screen-based reading has become ubiquitous and continues to grow. According to Pew Research’s 2012 study, individuals who read digital books are more likely to read more, and more frequently [63]; while their 2022 study reported that 75% of Americans read a book in 2022, with 30% reading digital e-books—a 5% increase from just three years earlier [25].

The growth in digital reading has prompted extensive research comparing screen-based reading to traditional print, with a divergence between subjective preference and objective performance suggesting a complex relationship. One study using eye-tracking and EEG found no significant differences in comprehension or cognitive effort between paper books and tablets, despite participants expressing a strong preference for print [46]. Notably, older participants showed shorter fixation durations when reading on tablets. Similar findings have been echoed elsewhere [1, 68], suggesting that subjective preference for print may not align with measurable performance differences. The enduring preference for physical books—often attributed to factors such as age, tactile engagement, and familiarity—persists even when readers acknowledge drawbacks such as physical size and weight, cost, or limited accessibility [18, 58]. In contrast, younger and/or more technologically fluent readers tend to show greater openness to digital formats. These patterns suggest that print preference may be more a product of habit and familiarity than the medium itself. To date, little is known about how readers perceive long-form reading in mixed reality, or how it compares to other digital reading devices.

In their book *Why Digital Displays Cannot Replace Paper*, Shibata and Omura [70] argue there are three primary factors undermining the prevalence of display-based reading: **1)** eye-unfriendly display characteristics (e.g., high contrast, flickering, glare); **2)** operational and physical constraints (e.g., displaying entire pages, page turning, device handling); and **3)** concentration disturbances (e.g., blinking cursors, intrusive icons, distracting menus). While these issues have consistently constrained digital reading for generations, technological advancements, intentional design, and the unique physical affordances of MR devices may be able to bring forward reevaluation of these factors.

2.2 Reading in Mixed Reality

The study of long-form reading in MR has received limited attention, though some research has specifically addressed dimensions of the experience. Pianzola et al. found that VR reading, using a 3D book model, can enhance intention to read via a serial mediation of transportation into the story world and affective empathy [61]. Similarly, recent work explored “symbiotic” VR reading experiences that use dynamic thematic environments to complement fictional texts. Although users reported enjoying the experience, their attention frequently shifted between the text and the immersive environment, leading to hybrid narrative interpretations [56]. While these studies centre on new forms of storytelling rather than traditional linear text-based reading, they nonetheless highlight the experiential potential of MR for narrative engagement.

Other research has focused on the technical and ergonomic considerations crucial for sustained reading in MR. Studies have shown that “dark mode” presentation (light text on dark backgrounds) can reduce visual fatigue and enhance legibility in both VR and AR HMDs [24, 44]. Text layout and positioning also matter: paragraph-style layouts in world-anchored positions outperform RSVP (rapid serial visual presentation) and user-fixed placements in terms of both comprehension and comfort [62, 65]. Optimal parameters identified for longer reading tasks in VR include a display distance of approximately 30.5 cm, text angles between 1.1°and 1.3°, and serif fonts rendered at 18 pt equivalency [45]. Additional work on field of view and curvature found that narrower views (90°) improve reading speed, and slightly curved displays (200*r*) enhance visual search accuracy compared to flat screens [71].

Further studies on reading in VR have examined caption-based narration in immersive VR [42], AR reading while walking [66], text displayed on 3D surfaces [75], and speed-reading interfaces [64]. While these studies provide important design considerations for interactive MR experiences, they have scarcely addressed how MR devices might support flow and usability in sustained reading.

2.3 Flow in Mixed Reality and Reading

Flow refers to a state of deep immersion in an activity, characterized by intense focus, a loss of self-consciousness, and distorted time perception [15]. Flow is closely tied to intrinsic motivation and typically arises during autotelic activities—those pursued for their own sake, rather than for external reward [55]. It emerges when there is a balance between perceived challenge and skill, and has been observed in domains ranging from sports and games to artistic creation and long-distance running [10, 13, 39, 67].

Recently, flow has been explored in MR research. Studies show that core flow preconditions, such as a sense of control and challenge-skill balance, can be achieved in immersive environments like VR [35]. Time distortion, a hallmark of flow, has also been observed among VR users engaged in gameplay [50]. Other studies have examined flow in mobile AR learning [6] and VR sports viewing, where spectators reported higher flow than with conventional displays [43]. These findings suggest that the immersive properties of MR displays can actively support the induction of flow across different activities.

Reading has long been recognized as a flow-inducing activity. Csikszentmihalyi called it "*perhaps the most often mentioned flow activity*" [17], while others have highlighted its close alignment with intrinsic enjoyment and deep cognitive absorption [73]. Flow during reading has been linked to narrative transportation and mental model construction [7], and is more commonly elicited by fiction than nonfiction—especially when the material is self-selected and personally meaningful [52]. Recognizing reading's unique cognitive and affective qualities, researchers have developed reading-specific flow measures, such as the Reading Flow Short Scale (RFSS) [73], designed to avoid performance-based framing and better capture immersive reading experiences.

The overlap between reading and flow, combined with MR's demonstrated capacity to induce flow in other domains, raises an important question: can MR support or enhance the experience of flow during long-form reading? This possibility frames our investigation, which seeks to evaluate whether immersive MR environments can deepen engagement, focus, and enjoyment in sustained reading.

3 Designing a Long-Form Reading Experience for MR

To investigate how MR technologies shape long-form reading, we designed a cross-platform reading system that enables controlled comparison across disparate devices. Our goal was not only to prototype a viable MR reading environment, but also to examine how key device properties influence the reading experience. This section introduces the conceptual framework that guided device selection, followed by a description of the MR reading environment developed to support immersive narrative engagement.

3.1 A Light Descriptive Framework of Reading Devices

Our primary interest is understanding long-form reading in mixed reality. To support this, we developed a simple descriptive framework to guide device selection and aid interpretation of results. Rather than categorizing devices by brand or capability, the framework distinguishes them by defining characteristics relevant to reading.

We began by considering a comparison between VR and AR head-mounted displays, but this immediately raised further design questions—for example, whether an AR device should use optical see-through or video see-through displays. To clarify these distinctions, we identified two independent design axes: *Form Factor* and *Display Technology*, yielding a 2×2 matrix (Table 2).

The Form Factor axis distinguishes between *handheld* and *head-mounted* devices. Handheld devices serve as a baseline and represent technologies commonly used for digital reading. Head-mounted devices, by contrast, enable hands-free interaction and include mixed reality headsets and smart glasses.

The Display Technology axis distinguishes between *emissive* and *reflective* displays. Emissive displays—such as LCDs and LEDs used in smartphones, tablets, and laptops—emit light either directly from pixels or via backlighting. Reflective displays instead rely on ambient or externally projected light. E-ink displays reflect light similarly to printed paper, while optical see-through AR displays redirect light through waveguides, allowing digital content to coexist with the physical environment. While emissive displays are often favoured for visual acuity, color saturation, and contrast in low-light conditions, reflective displays have been shown to reduce eye strain and support readability during prolonged use and in bright environments [28, 77].

The **Handheld Reflective** condition was represented by a Kobo Sage featuring an 8-inch E Ink display in a lightweight plastic chassis. This served as a representative baseline for long-form digital reading using reflective, paper-like display technology. The **Handheld Emissive** condition was a second-generation 11-inch iPad Pro, representing common phone/tablet reading experiences using a high-resolution, illuminated display. Our **Head-mounted Reflective** condition was the Magic Leap 2, a standalone optical see-through AR headset with displays supporting segmented dimming, allowing localized darkening of display regions to improve contrast—a property particularly relevant for text-heavy content. Much of it's processing is offloaded to an external *puck*, also reducing worn weight. Finally, a Meta Quest 3 VR headset represented our immersive, **Head-mounted Emissive** condition. To minimize distraction, video pass-through was disabled and participants were placed in a low-salience virtual environment composed of soft forms and muted tones. (see Table 1 for details)

A note about the framework — We do not present this framework as exhaustive, but as a pragmatic tool to guide device selection and interpretation. It motivated the inclusion of two

Condition	Device	Display	Resolution	PPI	Weight
Handheld Reflective	Kobo Sage (N778)	E Ink Carta 1200	1920 × 1400	300	241 g
Handheld Emissive	iPad Pro 11" (A2228)	LCD (LED-backlit)	2388 × 1668	264	466 g
Head-mounted Reflective	Magic Leap 2 (M90AA004)	LCOS (see-through)	1440 × 1760	~800	266 g
Head-mounted Emissive	Meta Quest 3 (S3A)	LCD (enclosed)	2064 × 2208	~1218	515 g

Table 1: Device specifications across experimental conditions.

baseline devices (the eReader and LCD tablet) alongside mixed reality headsets, enabling comparison across distinct form factors and display technologies. We acknowledge that devices are not uniform within these axes: for example, while both the Meta Quest 3 and Magic Leap 2 are head-mounted displays, they differ substantially in weight, with implications for comfort and usability; similarly, devices with emissive displays vary in optical characteristics that may influence visual comfort. Accordingly, while the framework structures our comparisons, it does not capture all device-specific properties—such as weight, thermal comfort, or optical design—which may independently shape long-form reading experiences.

We evaluated commercially available devices as integrated systems, accepting that such properties are inseparable from real-world use. Although the Magic Leap 2 has since been discontinued as a commercial product, it remains a representative example of a high-end optical see-through AR headset and was selected to examine the upper bounds of current AR reading experiences rather than to evaluate a specific commercial ecosystem.

	Reflective	Emissive
Handheld	eReader	LCD Tablet
Head-mounted	AR HMD	VR HMD

Table 2: Framework of properties matrix.

3.2 System

We developed a single, multi-platform reading application that delivered a consistent experience in software, interface, and text formatting across all devices. This allowed participants to engage with the same narrative text under each condition, minimizing confounds. Due to inherent limitations in the eReader's display and closed software ecosystem, we were unable to fully implement a customized application for that device. To address this, we opted to design our system around the eReader's interface, replicating its layout, font, and typesetting parameters for use in our application. The eReader was the only device that did not run our custom application, but our system was designed to mimic its reading interface as closely as possible. In this way, we maintained consistency across all relevant features (see Figure 1).

Our system was developed using web technologies (HTML, CSS, and JavaScript) to run within a web browser. The application has two primary views. First, the library view presents a grid of consistently styled, simplified book covers, with hover-activated tooltips displaying book details such as genre, publication date, and a short synopsis. Second, the reading view, accessed upon book selection, minimizes distractions by displaying only the text without a visible user interface or decoration. Text parameters, including font, text size, line spacing, and visible text area, were dynamically adjusted for each device to mimic the display of the eReader.

Text was rendered using the Georgia typeface, a serif font known for its readability even on small or low-resolution displays and commonly used in e-books [3, 27, 76]. In contrast to traditional print media, we employed an inverse colour scheme, or *dark mode*, with light text on a dark background—adopting near-white and near-black tones sampled from the eReader. This decision was informed by prior research indicating that dark mode enhances comfort, reduces eye strain, and improves readability [11, 21, 44]. When in an HMD condition, the reading pane was fixed approximately 30 cm from the user's head position, with a subtle angle easing to keep it facing the user as they moved (based on optimal parameters identified in prior research [45]), though it could be repositioned and pinned anywhere the reader preferred.

Both handheld devices could be either held or placed on an adjustable stand, allowing participants to adopt a reading posture they felt most comfortable in. For both HMDs, participants received assistance to ensure a secure and comfortable fit. Across all four device conditions, participants could navigate the text using either the device's native input (touch or gesture) or a Bluetooth keyboard modified with a physical overlay (constructed from cardboard and tape) to obscure unnecessary keys. Users were encouraged to choose whichever method they felt most comfortable with, and could switch freely at any time.

4 Study Design & Evaluation

To investigate how different device characteristics affect the long-form reading experience, we designed a within-subjects experiment in which each participant completed the same two tasks under each of four device conditions. The repeated measure in this design was device condition, with each participant serving as their own control across conditions. The order of conditions was counterbalanced using a Latin square design to mitigate ordering effects. Prior to the study, participants were asked to leave their phones and other potential distractions outside the testing room. They then received an overview of the study and the devices, provided informed consent, and completed a brief demographic questionnaire. All sessions took place in a quiet, well-lit room with only the participant and the experimenter present. Devices were placed on a table and introduced one at a time as participants progressed through the study.

4.1 Participants

Sixteen participants took part in our study and were recruited through poster and email advertisements and word-of-mouth. Our participant pool comprised 9 women and 7 men, ranging in age from 23 to 40, with a mean age of 28. We collected information on vision and previous MR use to ensure a range of users and to identify any potential discomfort or learning effects. Eight participants reported having normal vision, while eight reported corrected-to-normal vision, and none reported any known visual impairments. For MR familiarity, six participants had none or very limited experience, and the remaining ten had some experience with MR devices; with seven of them reported previously experiencing a degree of VR sickness [9].

Participants were also asked about their reading habits and language abilities. Ten participants spoke English as their first language, while six spoke English as a second language. All self-identified as fluent and proficient in English reading, and all study materials were presented only in English. Nine participants self-identified as *readers* (one who reads as an active hobby) while seven did not. The frequency of reading for pleasure ranged from daily to less than once per year, and all participants reported reading primarily in English.

All participants provided informed consent. The experimental procedure was approved by our university's research ethics board (file number REB-2023-190), and a gift card was provided as a thank-you for participation.

4.2 Tasks

The experiment consisted of two tasks: a short reading task (to measure reading performance) and a long reading task (to measure flow and user experience). The two tasks were designed to be completed sequentially for each condition. Before starting each condition, participants were introduced to the given device and its operation. After the short reading task, a brief break was given to collect measures and allow the participant to rest before proceeding to the long reading task.

4.2.1 Short Reading Task. The first task involved a short aloud reading assessment designed to evaluate participants' reading performance (i.e., to time and count any reading errors that arose from using the device). Participants were presented with a pre-selected passage of text and instructed to read it aloud in whatever manner was most comfortable to them.

To ensure consistency across all reading passages, we meticulously hand-selected and edited a series of texts to meet specific target criteria. Each passage was extracted from Grimm's Fairy Tales [32] and adapted to precisely 220 words across 11 sentences. Further edits focused on maintaining comparable difficulty levels across all versions. Specifically, each final passage averaged 1.2 syllables per word, had a Flesch-Kincaid Grade Level of 6.4, and a Flesch Reading Ease Score of 85 [26]. These edits were kept as minor as possible, carefully avoiding any impact on the original meaning, coherence, or structural integrity of the text, ensuring each passage remained fluid and complete when read aloud.

The selection of passages was balanced across conditions using a mutually orthogonal Latin square design. This ensured that each passage was distributed equally among participants across all four experimental conditions.

4.2.2 Long Reading Task. Following the short reading task, participants proceeded to a long reading task in which they were given unrestricted time to browse the system's library view and select a book. They were instructed to choose any book in the system that they would like to read for the remainder of the study. Participants were encouraged to explore the available options thoroughly and could ask for book recommendations or clarification. This selection process served a dual purpose: to allow participants to familiarize themselves with the device and its interaction mechanisms, and to ensure they chose a book that genuinely interested them for sustained engagement, as interest and enjoyment have been identified as antecedents of flow [20, 69].

Unlike the short passages, the book selection was not constrained by strict difficulty or thematic parameters. Instead, we offered a diverse collection of 20 narrative fiction books, with the primary criterion being sufficient length to support extended reading throughout the study. These books were selected from online user-curated reading forums (e.g., Goodreads). The goal was to provide popular and critically well-received novels, encompassing a range of reading levels and styles—both classic and contemporary—to ensure participants could find options aligned with their individual tastes and preferences. Participants were also asked not to select books they had already read, to avoid any potential bias or familiarity that might affect engagement.

To minimize stress and promote natural engagement and flow, participants were explicitly assured that their comprehension and memory of the book would not be evaluated. They were then instructed to read at their own pace while the experimenter left the room to ensure privacy. After 25 minutes-—an interval demonstrated to reliably induce flow in reading while remaining feasible for controlled lab studies [52, 54, 73]–the participants completed questionnaires about their experience with the device and the selected book.

4.3 Measures

4.3.1 Flow and Reading Experience. To capture the reader's flow and better understand their overall reading experience during the long reading task, we used the Reading Flow Short Scale (RFSS), a reading-specific flow questionnaire designed to sensitively measure flow in the context of reading. The RFSS is an adaptation of the Flow Short Scale (FSS) [48, 73].

The RFSS includes eight items spanning two subscales: *Absorption* and *Smooth Processing*, and omits the FSS items related to *Concern*, which apply only to competitive activities. *Absorption* reflects attentional involvement and engagement in the task, while *Smooth Processing* captures the sense of effortless progress and fluency during activity. Together, these dimensions represent core experiential aspects of flow in non-competitive contexts like reading [30]. Participants responded to each item using a 7-point Likert scale (1 = "strongly disagree", 7 = "strongly agree") following each long reading task, allowing comparison across the four device conditions.

4.3.2 Reading Performance. During the short reading task, performance was assessed through completion time and reading accuracy, quantified as the number of observed errors. For the purposes of this study, an *error* was defined as the omission or misreading of words, mid-sentence pauses exceeding one second, restarts of sentences or segments, or any disruptions that could plausibly affect reading continuity or comprehension. Minor verbal disfluencies such as stuttering or mispronunciations were not considered errors, as they were unlikely to stem from the reading condition itself. Both time and error counts were recorded live by the experimenter present in the room and later verified using videos to ensure accuracy.

No performance data (e.g., timing, behavioural logging, or video) were collected during the long reading task. Participants completed this task alone, with the experimenter monitoring unobtrusively from an adjacent room via two-way glass for safety and consistency. This setup was designed to minimize pressure and foster a more natural, immersive reading environment. Participants were explicitly encouraged to read at their own pace and were told that no comprehension test would follow, allowing them to read without concern for evaluation or performance.

4.3.3 Task Loading. The NASA Task Load Index (NASA-TLX), a validated and widely used subjective workload assessment tool, was used to understand the effect of each condition on task load after prolonged use [34]. The TLX captures six distinct dimensions of task load: *Mental Demand*, *Physical Demand*, *Temporal Demand*, *Performance*, *Effort*, and *Frustration*. For each dimension, participants rated their experience on a 21-point scale (0–100, in 5-point increments), with higher scores indicating greater perceived load—except for the *Performance* dimension, where higher values reflect lower perceived success (i.e., worse performance). To improve clarity, we inverted the *Performance* scores in our reporting so that higher values consistently indicate a greater level of the given dimension.

Our assessment used the "Raw TLX" (unweighted) method, following current practice, as weighting procedures are often omitted for consistency and interoperability across conditions and have been found to be ineffective [8, 33, 36, 57]. We computed the unweighted mean of the subscales to produce an overall workload score; this composite score captures general perceived workload while preserving insight into the relative contributions of each subscale. TLX ratings were collected immediately after the long reading task for each condition, while the experience was still fresh.

4.3.4 Post-Experiment Feedback. In addition to comments and questions made during and between trials, participants completed a final questionnaire and interview at the end of the study. The questions focused on subjective impressions of the reading experience and the device used. The questionnaire included a mix of open- and closed-ended items, as well as condition rankings across several experiential criteria. A brief interview followed the questionnaire, allowing participants to elaborate on their experiences and provide qualitative feedback on the devices and reading tasks. This combination of quantitative and qualitative measures aimed to capture a comprehensive understanding of the reading experience across conditions.

4.4 Statistical Analysis

All analyses were conducted in R version 4.4.1 [72]. Residual normality was assessed using the Shapiro–Wilk test. Repeated-measures ANOVAs were used when assumptions were met, with Greenhouse–Geisser corrections applied where sphericity was violated ($\varepsilon < .75$), followed by Holm–Bonferroni–corrected post hoc comparisons. For non-normal, severely non-spherical ($\varepsilon < .40$), or ordinal data, we used Friedman tests with Conover post hoc comparisons and Holm–Bonferroni correction. Spearman's rank correlations were used for exploratory analyses.

We report test statistics, exact p-values, and effect sizes (partial η_p^2, Kendall's W, $|\rho|$), with $\alpha = .05$. A post hoc sensitivity analysis indicates that with $N = 16$, the study was powered to detect medium-to-large within-subject effects, but not small effects. Accordingly, demographic and device-specific factors were not included as covariates and are instead discussed qualitatively as potential contributors.

5 Results

We organize our results by measure and task. We begin with performance analysis from the short reading task, followed by workload, experience, and flow measures from the long reading task, and conclude with overall participant feedback.

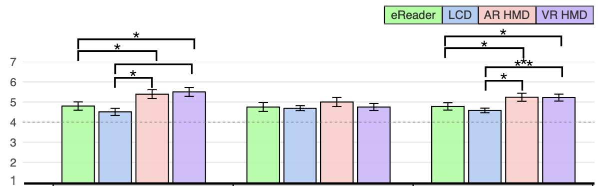
5.1 Flow Experience

We evaluated reading flow using the Reading Flow Short Scale (RFSS) across its three dimensions: *Absorption*, *Smooth Processing*, and a composite *Total* score (Figure 2). Significant main effects of device emerged for both Absorption and Total RFSS scores, but not for Smooth Processing.

Post hoc comparisons revealed consistently higher ratings for immersive displays. Both AR ($p_{\text{adj}} < .05$) and VR ($p_{\text{adj}} < .01$) elicited substantially higher Absorption scores than the LCD tablet. The eReader rated slightly higher than the LCD tablet, but this difference was not significant ($p_{\text{adj}} = .053$). The Total RFSS score mirrored this pattern: AR and VR significantly outperformed handheld displays (all $p_{\text{adj}} < .05$), while no differences emerged within form factors.

5.2 Reading Performance

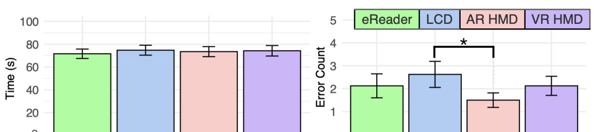
Analysis of performance during the short aloud reading task found no significant differences in completion time across the four device conditions. However, there was a significant difference in error counts, and post hoc analysis showed that the AR HMD resulted in significantly fewer errors than the LCD tablet ($p_{\text{adj}} = .028$); no other pairwise differences were statistically significant (see Figure 3).



	Absorption	Smooth Processing	RFSS Overall
F(df)	F(2.23, 33.38) = 12.45	F(2.44, 36.57) = 0.61	F(2.38, 35.68) = 8.16
η_p^2	0.454	0.039	0.352
p	< .001 **	0.580	< .001 **

Figure 2: Bar charts show the mean (± SEM) ratings of the Reading Flow Short Scale, with results of hypothesis testing in the tables.

These findings suggest that overall decoding and articulation ability remained consistent across devices, with a possible exception that the LCD condition may have introduced challenges that increased the likelihood of reading errors.



	Completion Time	Total Errors
W	0.119	0.182
χ^2	5.69	8.73
p	0.128	0.0331 *

Figure 3: Bar charts of mean (± SEM) performance results by condition. Tables show results of hypothesis testing.

5.3 Task Loading

Results from the NASA-TLX assessments revealed significant differences in perceived workload across the four conditions (see Figure 4). Post hoc tests revealed the following differences:

Physical Demand: The VR HMD was rated significantly higher than all other conditions: eReader (p_{adj} = .003), AR HMD (p_{adj} = .005), and LCD tablet (p_{adj} = .014). The LCD tablet was also rated as requiring more physical demand than the eReader (p = .030).

Effort: Participants reported significantly higher effort with the LCD tablet compared to both the eReader (p_{adj} = .011) and AR HMD (p_{adj} = .023).

Overall: The LCD condition yielded significantly higher overall task load compared to the AR headset (p_{adj} = .004) and eReader (p_{adj} = .007). VR was also rated significantly higher than AR (p_{adj} = .015).

These results highlight how device characteristics shape perceived workload. First, head-mounted displays showed divergent physical load profiles: emissive VR imposed significantly higher physical demands than reflective AR, suggesting that display technology mediates physical load despite a shared form factor. The LCD tablet, meanwhile, consistently elicited greater perceived effort and overall workload than both reflective displays.

Reflective technologies (both head-mounted and handheld) yielded lower subjective workload overall. AR, in particular, had the lowest mean workload (M = 20.68), significantly outperforming LCD and VR. Notably, although VR was the most physically demanding, it still scored lower than the LCD tablet on overall workload (M = 30.99 vs. 34.27), suggesting a dissociation between physical and cognitive burdens. These findings point to potential attentional costs associated with emissive displays, even when presented in a familiar form factor (i.e., the tablet).

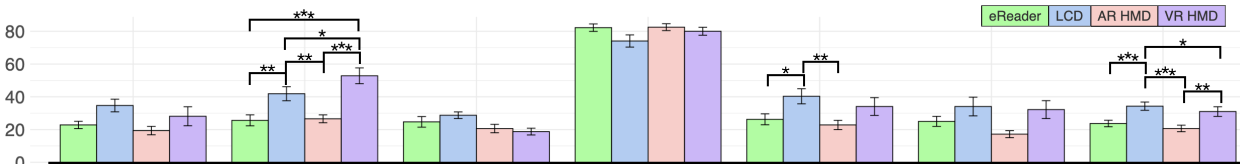
5.4 Device Rankings & Feedback

Participants ranked each condition in terms of *ease of use*, *comfort*, *future use*, and overall *personal preference* (see Figure 5). Significant differences were found for **Ease of Use** and **Comfort**. Post hoc comparisons revealed that the VR HMD was rated significantly lower than both the eReader and AR HMD for Ease of Use (p_{adj} = .003 and .026), and lower than the eReader for Comfort (p_{adj} = .024).

Reflective displays received the majority of top rankings across metrics. Notably, while ease of use and comfort showed significant differences, the more subjective measures of future use and personal preference did not, suggesting a more complex relationship between device traits and user preference.

These nuanced distinctions in user experience were further supported by participants' free-text comments. Nine participants mentioned direct drawbacks of conditions, as P2 shared: *"after [using the AR headset] holding the iPad was so annoying!"* and P12 added: *"the quest was so good until the end, then my eyes began to water"*. General physical barriers among HMDs were also noted, such as by P14: *"I was feeling fatigued or disoriented when taking off the headsets."* and P9 remarked: *"I feel like I was just wearing a helmet"*. For the VR HMD, people particularly noted the discomfort, including the headset being hot and heavy to wear for the 25-minute reading session. A few participants also mentioned that their loss of awareness of the physical environment was an annoyance; for example, when they wanted to shift position to get more comfortable, they would bump the table or feel like they might fall out of their chairs. P13 even mentioned that while reading in VR, they put the keyboard down and could not find it again, and they had been using it for turning the pages. Rather than remove the headset to find it, they opted for the hand gestures, which they found much less usable than the keyboard.

Despite these issues, both head-mounted devices showed situational promise. Several participants envisioned use cases like reading in bed or while multitasking with the AR HMD. P15 described their desire to read in AR while knitting: *"being able to peek down now and then without issue would be super helpful"*. In summary, participant feedback shows that form factor and display technology can lead to divergent experiences; people place different value on physical requirements, subjective experience, and situational benefits. Importantly, the thoughts on a particular device can be complex; some participants noted both the potential for a device and its usability



	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Overall
χ^2	7.5	26.75	7.67	6.6	13.56	7.12	24.52
W	0.156	0.557	0.16	0.138	0.282	0.148	0.511
p	0.058	< 0.001 ***	0.053	0.086	0.004 **	0.068	< 0.001 ***

Figure 4: Bar charts show Mean (± SEM) NASA TLX ratings by condition. Tables show the results of hypothesis testing.

issues. P13 felt that VR HMD was actually good for reading, but that the lack of comfort and other usability issues reduced its overall value for reading, summarizing with *"[the] quest would be good if it wasn't so bad"*.

In follow-up discussions, several participants directly voiced excitement for the possibility of improved ergonomics and comfort using the MR headsets. One participant, P11, described how their experience with persistent joint pain has impacted their enjoyment of reading; *"I sit down to read and after only a few pages I'm in pain, and I'm bending out my elbows, and pulling my neck, ..., so I just stop [reading]"*. They went on to say that being able to read while lying down, or in a more comfortable position, would be a significant improvement over traditional reading devices. This sentiment was echoed by P14, who said, *"I just want to read in bed without having to prop myself or my book up on [something]. I can just strap this [AR headset] on and lay back!"*.

5.5 Flow Correlations

To further explore each device's relationship with flow and the reading experience, we performed exploratory correlation analyses between participants' flow, task load, and subjective enjoyment ratings. These factors are believed to be positively conceptually linked with flow and its ties to intrinsic enjoyment, repeated activity engagement, and self-efficacy [73].

Overall, we found a significant positive correlation between participants' reading flow score (RFSS) and their overall enjoyment of the book, supporting the links between flow and reading enjoyment [14, 16, 52, 60]. When analyzed by device, significant flow-enjoyment correlations emerged for the **AR HMD**, **VR HMD**, and **eReader**, but not for the LCD condition (See Figure 6). These results indicate that the strength of the link between flow and overall enjoyment of long-form reading appears to be influenced by both the device's form factor and display technology, with stronger relationships observed in immersive and reflective reading environments.

Flow–task load relationships showed negative correlations. For the **AR** headset, *mental demand* was strongly negatively associated with flow; for the **eReader**, *temporal demand* showed a significant negative relationship; and in **VR**, *frustration* exhibited a moderate negative correlation. These task load–flow profiles suggest that different mechanisms may interfere with flow depending on the device: *mental load* in AR, *temporal interruptions* in eReaders, and *frustration* in VR.

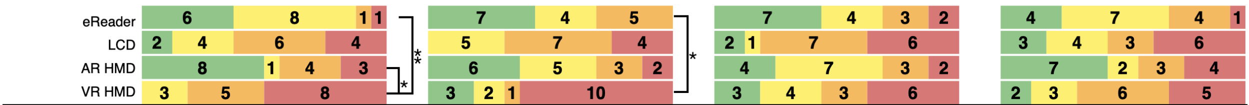
5.6 Summary of Findings

- MR devices elicited significantly higher flow than both the LCD tablet and eReader during long-form reading.
- Task load was rated significantly higher for the LCD tablet and VR HMD compared to both the AR HMD and eReader; the LCD tablet showing higher task load than the VR HMD.
- Participants made significantly more reading errors on the LCD tablet than with the AR HMD.
- The VR HMD was rated significantly less comfortable than the eReader, with frequently cited issues of heat and weight.
- Overall preference favoured the AR HMD and eReader over the VR HMD.

6 Discussion

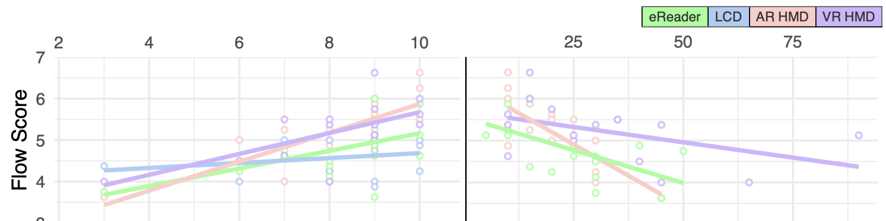
Overall, our findings provide strong evidence that MR devices can support flow in long-form reading. Both AR and VR headsets yielded significantly higher absorption and overall flow than handheld devices, aligning with prior work linking immersive technologies to presence and engagement [19, 47, 61]. While immersion reflects the sensory and perceptual qualities of an environment, flow captures a state of optimal psychological engagement. Our results suggest that MR supports deeper narrative engagement not only through immersive presentation, but also through affordances such as hands-free use and flexible posture, which may reduce physical effort and support sustained focus.

Among the four conditions, the AR HMD and eReader were most preferred and received the lowest workload ratings. These were also the lightest devices in the study, suggesting that device weight plays a meaningful role in comfort during extended reading. In contrast, the LCD tablet and VR headset—both substantially heavier—were rated lower in comfort and imposed higher task load. Weight-related discomfort was frequently mentioned by participants as "annoying" and "distracting", and led to compensatory behaviours such as propping the tablet on a surface or using one hand to offset the weight of the VR headset. Despite these differences, reading performance was largely consistent across conditions, with an exception in the LCD tablet, which produced significantly more reading errors.



1st 2nd 3rd 4th	Ease of Use	Comfort	Future Use	Personal Preference
W	0.267	0.233	0.145	0.081
χ^2	12.82	11.18	6.97	3.90
p	0.005 **	0.011 *	0.073	0.272

Figure 5: Bar charts of the count of rankings for each condition. Table shows the results of hypothesis testing.



	Book Enjoyment				Task Load		
	AR	VR	eReader	LCD	**AR**: Mental	**eReader**: Temporal	**VR**: Frustration
ϱ	0.81	0.59	0.53	0.20	-0.62	-0.59	-0.50
p	<.001 **	0.017 *	0.036 *	0.470	0.011 *	0.016 *	0.05 *

Figure 6: Correlational analysis of flow with (a) Enjoyment and (b) Task Load subscales (only significant results shown).

Notably, the VR headset elicited high flow scores despite poor comfort and workload ratings. Although participants reported heat and weight-related discomfort during the 25-minute session, none withdrew, and several highlighted the headset's immersive potential. This suggests that physical discomfort does not necessarily preclude strong engagement, and that more ergonomic VR hardware could better support long-form reading in the future.

The LCD tablet performed poorest across most measures and did not support flow to the same extent as the MR headsets. Despite its technical capabilities, the tablet's backlit display, susceptibility to glare, and hand-held weight made it both visually fatiguing and physically uncomfortable. Similar issues were observed with the VR headset, which also relies on a backlit display. In contrast, the eReader and AR HMD were rated as most comfortable and were substantially lighter. Although not explicitly captured by our framework, device weight appears to be a critical factor in long-form reading, as it constrains posture and limits how long positions can be comfortably maintained [12, 38, 59].

The AR HMD, in particular, shows strong promise for long-form reading. It combined high flow scores with low workload and high comfort. While some participants reported minor eye strain, this was less pronounced than in the VR or LCD conditions. The Magic Leap 2's high-quality see-through display may contribute to this relative comfort, offering an alternative to conventional backlit screens. Additionally, the see-through, hands-free design enabled users to shift posture, remain aware of their surroundings, and envision scenarios such as reading in bed or during light activities, where unobtrusive access to text is especially valuable.

6.1 Concerning the Framework of Digital Reading Technologies

To better characterize this open research space [29, 31], we developed a simple descriptive framework based on two axes: display type and form factor. While not exhaustive, this framework guided device selection across display technologies and revealed patterns that extended across form factors. In particular, we found that participants considered reflective technologies more comfortable for long-form reading. We believe that future work can build on and extend this simple framework to encompass additional properties of reading devices, in order to better characterize the factors that affect reading experiences, especially as new technologies, including new display types, form factors, and other characteristics, continue to emerge.

6.2 Longer-Form Reading

Much prior work on MR reading has focused on short-form text and brief interactions [22, 61, 65], whereas this study examines sustained engagement with long-form narrative texts. Our long reading task was limited to a 25-minute session—an interval adapted from prior work and sufficient to support engagement and the induction of reading-related flow [52, 73]. However, real-world long-form reading often unfolds over substantially longer durations and across repeated sessions with the same text.

As a result, our study may not capture longer-term effects such as cumulative visual fatigue, evolving comfort, or changes in device preference over time. Some challenges may lessen with familiarity or improved hardware, such as how cybersickness is reduced with more experience [23, 37], while others—particularly those related to emissive displays or physical factors—may intensify with prolonged use. Longitudinal or in-the-wild studies are therefore needed to examine how reading behaviour, workload, and flow evolve with repeated everyday use. Whether the patterns observed here persist, attenuate, or invert over longer time scales remains an open question.

Additionally, the use of partially-open-ended book selection introduces variability in narrative engagement, as factors such as genre, pacing, and familiarity can influence reader motivation and, in-turn, flow [41]. While curated texts were selected to maintain broadly comparable narrative structure and readability, individual differences in content preference may still have affected subjective experience measures. As such, observed differences in engagement should be interpreted as reflecting an interaction between display condition and reader–text fit, rather than device effects alone.

6.3 Limitations and Future Work

6.3.1 Exclusion of Physical & Audio Books. Importantly, our study did not include other book formats—most notably physical books and audiobooks. First, we excluded audiobooks, as they constitute a fundamentally different medium: passive, performative, and non-visual, clashing with our primary interest in the visual and interactive aspects of mixed reality technology. However, with the rise in popularity of audiobooks and podcasts, and given that they share some properties with text-based reading, there is exciting potential for future work to compare—or combine—audio and text experiences using similar tasks and setups.

Second—and perhaps more conspicuously absent—are physical books. While we considered this omission carefully, we ultimately felt physical books were too dissimilar to offer meaningful comparisons within our framework. Practical constraints in layout, typography, and physical interaction, combined with potential bias toward physical books and against technological intervention [5, 51] exclude them and focus on four conditions we could compare more directly. Nevertheless, now that our work has established that MR devices can better support flow than other digital reading devices, it would be valuable for future work to compare MR with physical books.

6.3.2 Participant Pool and Generalizability. Our participant pool was largely recruited from our university campus, and while we attempted to recruit a diverse range of participants, the resultant predisposition or interest in technology may limit the generalizability of our findings to a broader population. Further, this might be particularly relevant because older adults spend substantially more time reading than younger adults (US data) [63, 74]. Future work should consider targeting a more diverse participant pool, including individuals from diverse backgrounds, to better understand the impact of MR devices on the reading experience across demographics.

6.4 How Spatial Should Reading Be?

In this study, we presented an MR reading experience intentionally designed to parallel traditional reading media, minimizing introduced novelty to enable close comparison across platforms. While this was a deliberate choice, the broader possibilities of reading in mixed reality extend far beyond conventional paradigms—from rethinking reading interfaces and controls, such as pagination and spatial layouts, to inventing new modes of interaction and narrative structure [40].

Having established that MR is not only a viable reading platform but one that may even enhance flow and engagement, we believe this baseline opens the door to more speculative and expressive forms of spatial reading. Future work could embrace the affordances of MR to create novel reading experiences—ones that leverage spatial capabilities not just as a container for text, but as an active component of storytelling and reader engagement. Spatial interfaces for consuming, interacting with, and experiencing text remain underexplored and invite richer design investigations.

7 Conclusion

This work examined how people can attain a state of flow—the optimal engagement with text—in long-form narrative reading using digital reading technologies. Using a within-subjects, cross-condition design, we compared flow, reading performance, and subjective experience across four devices representing distinct points in our framework: form factor (handheld vs. head-mounted) and display technology (reflective vs. emissive). We find that the spatial, visual, and ergonomic affordances of mixed reality headsets better support flow than more common reading technologies. Our findings suggest that while reading ability remained consistent, user experience varied substantially across conditions. Reflective displays consistently elicited lower perceived workload than emissive ones, and the AR headset (Magic Leap 2) in particular struck a compelling balance: offering high narrative absorption compared to handheld options, and greater comfort and flow than the more cumbersome VR headset. These results highlight the complex trade-offs between immersion, usability, and task load in extended MR reading.

Together, these findings offer important guidance for the design of spatial user interfaces for narrative media such as long-form text. They underscore MR's potential to enrich reading experiences through immersion and presence, while also revealing that physical comfort, interaction modality, and visual ergonomics are critical to sustaining that engagement. We envision future MR reading systems that fully exploit these strengths—hands-free reading, flexible spatial layouts, and narrative immersion—while addressing current limitations in device weight, display strain, and input fatigue. As spatial computing matures, reading may evolve beyond the constraints of flat screens and into environments where stories unfold not only across pages, but across space. Our results suggest that if designed thoughtfully, MR could become not just a viable and enjoyable reading platform, but a uniquely compelling one.

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Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009