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Virtual and augmented reality text environments support self-directed multimodal reading

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ABSTRACT
Virtual (VR) and augmented reality (AR) technologies are two of the fastest-growing technologies anticipated to peak this decade, with a gap in research to understand the new multimodal affordances for teachers to support students' self-directed interactive reading. This research aimed to understand early adolescents' experiences of reading multimodal texts containing written and spoken language and 3D imagery in VR and AR text environments. The study applied thematic coding and multimodal interaction analysis to understand how students engaged with reading 3D, multimodal, non-fiction VR and AR texts in educational games. The findings attend to the following reading practices exhibited by learners: (i) connecting new knowledge to the known, (ii) recalling information; (iii) resolving cognitive disequilibrium, (iv) using haptic interactivity to navigate text pathways, and (v) using selective attention to filter information. The students followed varied text pathways while demonstrating cognitive disequilibrium and resolution when responding to multilayered attentional cues and text pathways, with students encountering multiple cuing systems with VR and AR texts that use different navigation aids than those offered in books. Reading multimodal texts across modes involved attending to several modes, while backgrounding others, with opportunities for extensive haptic interactivity, and requiring selective attention in extended reality environments.

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Introduction

Extended reality (XR) technologies are rapidly advancing, offering new learning potentials and affordances for multimodal reading and writing: that is, reading and writing using two or more modes, such as written words, images, audio, and haptics (Mills et al., 2024). Extended reality technologies include three clusters of technology: virtual, mixed, and augmented reality (Mills, 2022). Virtual reality (VR) technologies maximise immersion in three-dimensional, simulated worlds where the real world is blocked from view (Mills et al., 2022). While virtual reality learning is not new, understanding how early adolescents read in virtual reality environments is a key gap in literacy research. Early adolescence is a critical stage for providing formal support with multimodal and digital texts (Golan et al., 2018). Unlike print and digital books, virtual reality texts are an immersive, three-dimensional virtual space that the user can move within corporeally, offering a sense of presence – of being

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in there – in the narrative. Usually supported by a head-mounted display and motion-tracking, the virtual text involves haptic interactivity and feedback that also differs from books (Mills, 2022).

Mixed reality (MR) technology refers to applications that allow for blending the virtual and the real within the user's immediate environment, including haptic interaction with virtual objects that can be manipulated through haptic, voice, or eye movements within the real world. Recent examples of mixed reality technologies include smart glasses, such as the Microsoft Hololens 2, Meta Quest Pro or Apple Vision Pro, which use semi-transparent, holographic 3D imagery and audio viewed through a head-mounted display. Mixed reality devices have been previously researched to understand the affordances for students' multimodal storytelling (Mills & Brown, 2023), and to encourage interdisciplinary education within a virtual environment (Veer et al., 2022).

Augmented reality (AR) overlays virtual objects over the users' view of the real world, often through a browser or camera application (Mills, 2022). A more well-known form of augmented reality technology is AR product advertising in which purchases can be superimposed over the user's real environment through an internet browser, however, uses for teaching reading include interactive e-books with 3D virtual overlays and models that enliven narratives by overlaying animations and virtual agents – virtual characters who exhibit lifelike verbal and non-verbal behaviour in the users' real world.

Augmented reality technology is the most accessible extended reality technology (compared to VR and MR), due to the popularity of mobile devices, with smartphones and tablets able to be held over books or physical learning objects to connect digitally to interactive 3D augmented reality content and models (Fan et al., 2020). Due to its accessibility, augmented reality is the fastest-growing virtual technology worldwide (Moro et al., 2023), yet there is a gap in research to understand how readers interact with AR for reading. Augmented reality requires attending to multiple compositional layers that combine virtual and real elements, different forms of haptic engagement, and new operational skills than those used for other digital media formats (Blevins, 2018).

The current research explored learners' experiences of reading digital texts about outer space exploration supported by two different virtual reality (VR) and augmented reality (AR) applications to understand students' reading interactions and the new capabilities required to navigate these 3D multimodal, interactive text environments. This is timely because virtual and augmented reality texts are now readily accessible to many for educational use, digital gaming, and business interactions (Ok et al., 2021), and have significantly different characteristics than multimodal texts depicted in 2D digital formats, with affordances for enhanced spatial knowledge, enhanced empathy, experiential learning, and stronger transferring of knowledge (Southgate et al., 2019).

Multimodal Reading in VR and AR text environments

Multimodal reading in virtual and augmented reality environments involves multiple reading pathways that differ from the typical predictability of printed books (Mills et al., 2023). In these digital contexts, students need to self-regulate their attention to filter out distractions and make conscious decisions about reading directions (Kieffer et al., 2013). Digital reading in virtual and augmented reality environments involves new forms of haptic and bodily interactivity, including locomotion in a virtual space (VR), and moving physically to locate virtual objects using AR (Dunleavy et al., 2009; Mills et al., 2023; Mills & Brown, 2021). Some of the noted features of these extended reality text environments include 3D information displays (VR and AR), immersion in the text (VR), and compositional overlays that involve real and virtual elements (AR) (Blevins, 2018). Digital texts also lack the same kinds of material anchors to aid memory that books offer (Golan et al., 2018), while presenting new forms of haptic interactivity through hand controllers, in-air haptics, or holding and turning AR learning objects that differ to other forms of 2D screen-based media (Mills et al., 2023). Critically, the use of XR reading is increasingly needed in higher education and workplaces, crossing all disciplines (Mills & Brown, 2023).

While research on VR and AR is not new, only a small proportion of research on these technologies focuses on literacy learning at the school level, while VR in STEM, health, and higher education is simultaneously growing (e.g. Moro et al., 2021). Virtual reality experiences have been researched as an instructional strategy for promoting reading comprehension (Paquette et al., 2020), while AR-based reading materials provide stronger support for EFL learners' reading comprehension and enjoyment compared to conventional book reading (Ebadi & Ashrafabadi, 2022). Additionally, emergent research of AR and VR technologies that are driven by a language focus has involved commercial applications that target limited rudimentary literacy skills, such as phonics and spelling, while many studies of AI tools are funded by the technology development industry, typically with limited connection to the teaching of reading in the curriculum (Fan et al., 2020; Ok et al., 2021). Importantly then, it is imperative to understand how students interact with multimodal reading in VR and AR text environments, and what reading capabilities students need to apply in these digital contexts.

Materials and methods

This section summarises the research methods applied in this study, including a description of the methodology, ethics, research question, site and participants, data collection, and data analysis. This qualitative research involved collaboration between researchers and teachers to plan virtual and augmented reality reading experiences that were integrated into the regular curriculum with adolescents in a secondary school. Observational research methods were used to investigate the students' multimodal reading in VR and AR environments. Data collection combined video recording, screencasts, think-aloud interviews, and teacher interviews, while multimodal interaction analysis was applied to the video and screen-based data sets, and thematic analysis to the discourses to understand the complexity of reading interactions across materials and modes (Friend & Mills, 2022).

Research question

The following research question was asked in the context of early adolescent students using VR and AR textual practices in secondary school:

> How can students interact with multimodal reading in VR and AR text environments, and what reading capabilities can students apply in these digital contexts?

The importance of understanding learners' reading interactions is critical, particularly to know how teachers can support students' advanced capabilities to navigate complex VR and AR texts, locate information, connect new to existing knowledge, and selectively filter distractions and inputs in 3D multimodal and immersive textual environments.

Site and participants

The participants in this research were from an independent, P-12 school in Queensland, Australia, a multi-age class of students aged between 12–15 years (Years 6-10, n = 12), and their two teachers. The focus on early adolescence is consistent with the study aim to address a gap in XR research for this age group. Interaction with multimodal texts is imperative in the national curriculum (ACARA, 2023), while VR headsets are recommended for users who are 12 years old and upwards (Australian Government, 2023). The school was culturally diverse, supporting the broad utility of the findings, with 37.9% of the local population born overseas (New Zealand, England, China, South African, and Japan), and 62.1% born in Australia. 40.7% have both parents born overseas, higher than the state (27.9%). Median income for households was consistent with the state and national average (ABS, 2021). Two teachers of the students, one male and one female, collaborated in planning the learning experiences with the research team and participated in audio-recorded, semi-structured teacher interviews about the reading experiences in XR environments.

Research ethics

The Australian Catholic University Human Research Ethics Committee (ethics approval ACU 2018-97H) approved this study in accordance with the National Statement on Ethical Conduct in Human Research (Australian Research Council, 2018). Students and their caregivers gave their consent to be digitally recorded using video to be published using pseudonyms.

Learning experiences

Over one school term, the two teachers collaborated with the researchers to design educational activities following the Australian Curriculum objectives for Digital Literacy (e.g. honing abilities in media technologies to investigate and locate information), Media Arts (e.g. employing software tools for text production and to convey ideas), and English (e.g. making multimodal texts for different audiences and contexts) (ACARA, 2023).

VR and AR software were selected to complement a science curriculum unit on space and a related science fiction writing module, aiming to support student engagement with the complexity of space science, comprehension of abstract concepts, and inspire curiosity. Teachers introduced students to the topic through their usual classroom lessons. Supported by a Meta Quest Pro (Reality Labs, Redmond, WA) head-mounted display (HMD) – which blocks the outside world from view – and hand controllers, students utilised a VR application "Titans of Space" which provides high-immersion 3D simulations of celestial phenomena incorporating written, visual, audio, and animated texts. Students interactively explored concepts such as planetary orbits and astronomical measurement. An AR object, Merge Cube, offered additional interactive experiences with visually animated models and written text about the solar system, and students used a second AR software, AR Makr (Line Break Studio, New York), to compose stories about aliens and other science fiction narratives. The focus of this paper is on the digital reading undertaken with the AR and VR science activities.

Data collection

Data collection was conducted over three weekly visits and involved two main data sets to understand multimodal reading in VR and AR: student learning data and teacher perspectives gathered through semi-structured interviews. A unique combination of video and screen-record methods documented students' VR reading, accounting for user interactions in both the virtual and material worlds. Video-recorded think-aloud interviews were recorded during students' interactive reading [See sample video: https://drive.google.com/file/d/1TosJS1SzfM85z1tDZ-f9ysm5fQbikYOOa/view. This was supported with screen capture to provide learning support to the students, and to stream learning interactions to a computer screen using the OBS Studio (2024). The OBS screen capture recordings were collected of 12 students' VR interactive reading (approximately 5.8 h total, average 31 min each) [See sample OBS: https://drive.google.com/file/d/1aHZNYTnK-kkduwZ63qx55QOVBjWW3XTh/view]. OBS Studio facilitates the sharing of the student experience in real-time and allows for subsequent detailed analysis of the recording (Garcez et al., 2011).

The research team collected 12 think-aloud interviews and video recordings (6.6 h total). These semi-structured protocols inquire about students' thought processes during the reading experience, rather than relying on more distant recollections (Hevey, 2020). Participants were asked questions in response to their real-time actions as they engaged with text, for example, "What draws your attention?", "What are you looking for?" In the think-aloud example below (Figure 1), the researcher prompts the students to share their thoughts in response to the text.

Researcher:	Does it sound like it would be a good place to live?
Student:	No.
Researcher:	Why's that?
Student:	Because for three months, you're just constantly night and it's really, really cold, and then in the day, you're just really, really hot. I can also see the moon over there.

Figure 1. Sample think-aloud excerpt.

To understand the new multimodal reading skills that students need in augmented reality textual environments, the researchers collected 12 video-recorded, semi-structured interviews about AR application use for literacies, recorded during and after the AR learning experiences. Screen recordings from the iPads were also used to build a record of the students' screen interactions [View AR: Click to View]. Video recording was used because it permits replaying observational data in situ for accuracy, while screen recording permits the multimodal analysis of the students' textual engagement (extended here for use with mixed reality) (Mills & Brown, 2023).

Semi-structured, audio-recorded interviews were also conducted with the teachers after the student learning activities. Semi-structured interviews are an established, effective method to explore participants' thoughts about a topic through flexible open-ended and predetermined questioning (DiCicco-Bloom & Crabtree, 2006). Teachers were invited to reflect on the student activities and the advantages and challenges of XR technologies for literacies, e.g. "What do you see are some of the advantages of VR reading and gathering information?"

Data analysis

Reflexive thematic analysis was used to code the students' VR and AR think-aloud interview transcripts (n = 12) in NVivo12 (QSR International). This interpretative approach sees coding develop through researchers' reflective engagement with a qualitative dataset where patterns are understood in the context of the theoretical research focus (Byrne, 2022). Consensus coding was used in which the researchers coded the same data, discussing the themes and reaching an agreement collaboratively, removing the need for inter-rater reliability measures (Ho & Limpaecher, 2023). Coding was initially organised into two broad categories: student focus (attention) and information-seeking behaviours. Subsequent themes were developed inductively based on the reading behaviours common to the participants. Figure 2 below presents the interview themes with sample student quotes, accompanied with a brief context statement to situate student actions.

Multimodal interaction analysis was then applied to understand the unique digital reading environment, including how modes of communication work together – written text, image, haptic, verbal, and auditory. This multilayered approach aims to analyse meaningful interaction through focusing on more than verbal speech alone and supports analytic attention on the multiple sign systems students encounter while reading in VR and AR (Friend & Mills, 2022).

Students' multimodal text interactions were analysed by examining verbal speech alongside their non-verbal actions and the textual modes of written text, 3D visuals, and audio. Analysis of the video and OBS recordings involved constructing multimodal transcripts which included descriptions of haptics and interaction. In Figure 3 below, a sample VR multimodal transcript illustrates the students' use of multiple modes to understand the planet Neptune.

Multimodal transcripts were similarly constructed for reading with the AR object, attending to student speech and action (see Figure 4).

Interview Theme	Example	Action
Connecting to the known	"It's based [on] a Greek goddess of agriculture". "They're craters, most likely".	Chloe refers to Ceres and Io. (VR)
	"…oh, that's even a satellite. Elon Musk, is that you?"	Nash views an animated model of Earth with orbiting moon and satellite. (AR)
Questioning & cognitive disequilibrium	"The volcano looks so small. In the VR it looks so small. I wonder how big it would be if you were to stand next to it in real life".	Oliver reflects on Olympus Mons. (VR)
	"What are these? Mars has asteroids?"	Nash views an AR model. (AR)
Recall	"I remember that Jupiter is… 98 per cent gas and that Mars's days are 38 minutes longer than our days".	Oliver recalls information. (VR)
	Zach correctly selects "8 planets and the Sun" to describe the solar system.	After using the AR, Zach completes a brief content quiz. (AR)
Haptic interactivity	"I'm going to go towards the sun".	Zach chooses where to explore. (VR)
	"…you don't sort of realise how big the Earth is…".	Archie used simulations which communicated a sense of scale. (VR)
	"I think it's way better than just looking at a photo, because then you can move it around to wherever you want to. If you want to look underneath it, on top, sides…".	Zach turns the Merge Cube in his hands to alter the view of the AR model. (AR)
	"…you can get more of an idea of how they (the planets) move".	Riley turns the Merge Cube and expands the AR model. (AR)
Selective attention		
• Written text & images	"…the sun is 860 light years [away]…" The student shifts their gaze for visual confirmation of the distance.	Noah reads written text. His focus shifts between written text and visuals. (VR)
• Animated visuals	"…he's (the virtual agent) explaining it, going up to it to show it…".	Emma focuses on an animated virtual agent while learning. (VR)

Figure 2. VR and AR student think-aloud interview themes, sample quotes, and actions.

Reflexive thematic analysis was applied to teachers' semi-structured interviews (n = 2) using NVivo 12 to identify common themes (Byrne, 2022). Concurrently, the interviews were viewed as individual case study reflections and thematically analysed as separate texts to compare them. Word frequency queries in NVivo were utilised to corroborate the thematic coding processes. The resulting frequencies are illustrated below as word cloud visualisations (see Figure 5 below). The analysis of teacher interview themes involved the use of word clouds to visualise the relative importance of high-frequency terms in the teachers' interview discourse. Visual representation methods have gained credibility as effective data analysis and presentation, bolstered by advancements in tools and software for digital data (Mills, 2019). In word clusters, the size of the font indicates the words and concepts that most commonly occur. The queries used "specialisations" in NVivo to group related terms, facilitating the identification of frequently occurring themes within the dataset, and confirming the thematic coding.

Results

The results are organised by the overarching themes that emerged in the analysis of students' VR and AR textual interactions: (i) connecting new to the known; (ii) recalling information, (iii) cognitive disequilibrium and resolution, (iv) haptic interactivity, and (v) selective attention.

Selective attention: Nash shifts his attention between written text and visuals, while considering the written information.
VR Game: Titans of Space

Written text	Visual	Action	Verbal	Audio
"NEPTUNE: Ice giant #2" - Distance from Sun: 30 AU - Volume: 57+ Earths - 14 known moons Has very active… [etc.]" The colour of the dashboard text is green.		Nash points the hand-controller laser to the written text on the spaceship dashboard and speaks aloud as he reads (57+ earths).	Nash reads aloud from the dashboard "Neptune. 57 plus Earths".	No music. No virtual agent.
When the student looks up at Neptune, there is a label: "NEPTUNE 49,528 km".	The planet Neptune and the spaceship dashboard are visible in the centre of the student's vision.	He looks up to the planet Neptune.	He looks up at the planet. "So, this is 57 Earths? Wow, that's big".	
The colour of the label text is yellow.	Numerous buttons are visible on either side of the dashboard and are multi-coloured. Buttons have a combination of symbols and written text, e.g. "[magnifying glass]" and "READY".	Nash looks back down at the spaceship dashboard. He points the hand controllers towards the written text on the dashboard and continues reading.		

Figure 3. Sample multimodal transcript.

Cognitive disequilibrium: Zach verbalises that he does not understand the functioning of the Mars Rover components.
AR Merge Cube

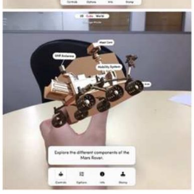
Written text	Visuals	Haptic	Verbal	Audio
The AR model is labelled with black text on a white background, e.g. "UHF Antenna". Text prompts and menu icons and text are visible on screen.	  Parts of the Rover are animated, indicating how they move.	Zach holds the physical Merge Cube box in one hand. He turns the box to view the various components of the Mars Rover model.	"It's cool. I have no idea what it means, though. Like, the things (the components of the Mars Rover). I know what that does and that does".	There is no electronic voice in this section.

Figure 4. Sample multimodal transcript.

Connecting new to the known

Learners' self-directed multimodal text interactions in immersive VR and AR environments were analysed to understand what new multimodal reading capabilities students applied in these digital contexts. An important pattern was the frequency of instances in which students verbalised the connections they made between prior knowledge and new multimodal information. The ability to connect the "new" to the "known" is a process that is necessary for reading comprehension as learners connect or assimilate new information (Dong et al., 2020; Kalantzis & Cope, 2005). For example, Oliver used the navigation button to move his spaceship away from Pluto to orbit the sun. As the spaceship traversed heavenly bodies and debris, a small planet appeared on the horizon.

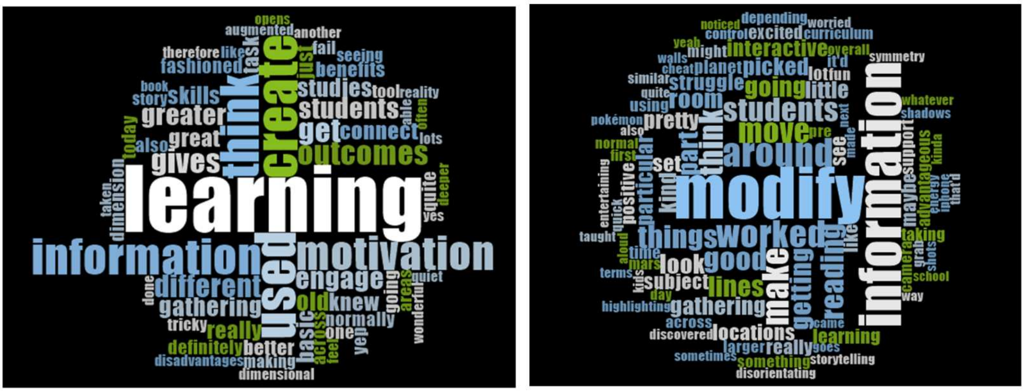


Figure 5. Word cloud teacher interviews – Johanna (left) and Michael (right).

Recognising the planet, he exclaimed excitedly: "There's the Earth. I see the Earth!" Focusing his attention on the earth's topography he then actively searched for his location in the real world: "I can see Australia. Whoa!"

In another example, Chloe recounted her prior knowledge about Greek deities and astronomy to assimilate the multimodal representation of Saturn's moons. In her field of vision were the labelled moons Titan, Rhea, Dione, Tethys, Enceladus, Pan, and the planet Saturn in the distance (see Figure 6).

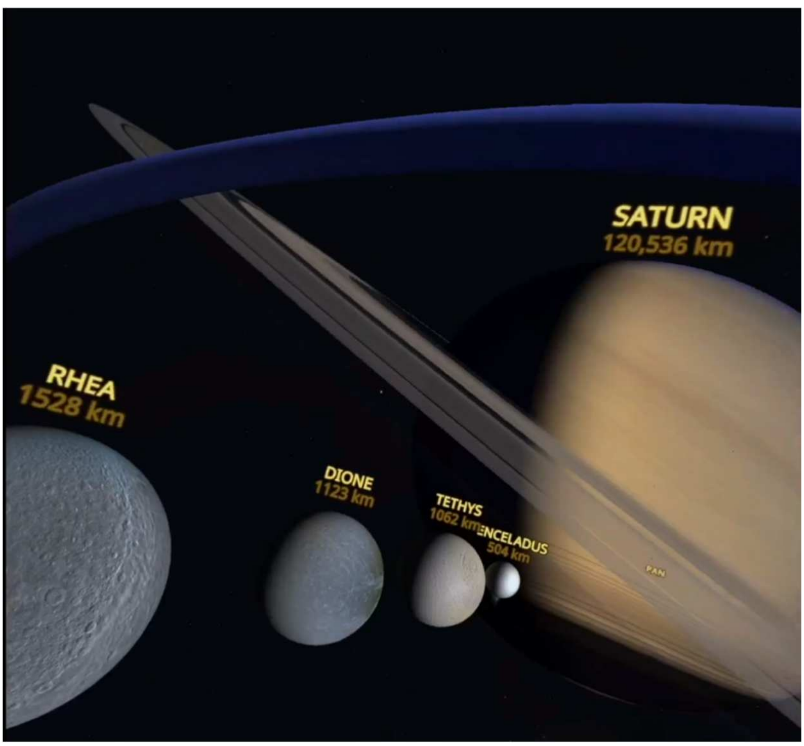


Figure 6. Saturn's moons in Chloe's field of vision.

Linking the 3D representation of labelled moons to her prior knowledge of Greek mythology, she volunteered: "These moons and the planets that have been discovered have all been named after Greek deities. Such as, I know Rhea and Tethys – they were both Greek gods". Chloe then noted how the game accurately depicted the texture, relative size, and diameter of the moons, as she simultaneously processed the new information, retrieving prior knowledge, and integrating these two types of information into an updated mental model of Saturn's moons.

In VR, after visiting Uranus and Neptune, the autopilot transported another student, Sophia, to the stars Pollux, then Rigel. After observing the orange star, Pollux, and comparing it to the blue-white colour of Rigel, she questioned: "It's a star? … Why is it blue then? … Is it blue fire?" She then applied her knowledge of the colour of fire from her prior experience: "So you can get blue fire, like on cooking stoves, since they are a lot hotter". Sophia connected this prior knowledge to accurately infer new information about Rigel's temperature from its depicted colour: "Because the hotter the fire is, the brighter it gets".

Similar instances were observed in the students' reading of the AR Merge Cube. Zach sought clarification of terminology by connecting new to known information about Saturn, which he had selected from the manipulable 3D model (see Figure 7).

Zach counted the visible moons in the animated model. He selected the information icon and then read the written information: "Rotational Period: 10 h 39m". Zach queried aloud: "So when it says, "rotation period", does it mean hours in a day?" He confirmed this conjecture by drawing on familiar knowledge of the earth's rotation around the sun: "Mm … like, how ours is 24 hours". In each of these instances, the students actively acquired new multimodal information from the three-dimensional VR and AR texts, activating their prior knowledge to assimilate novel information within an expanded schema or existing network of knowledge of the solar system.

Recalling information

Learners were able to recall new information they had comprehended in their self-directed interactions with multimodal VR and AR texts. During the VR think-aloud, the researcher would prompt the students to share newly acquired information: "Are you learning something new

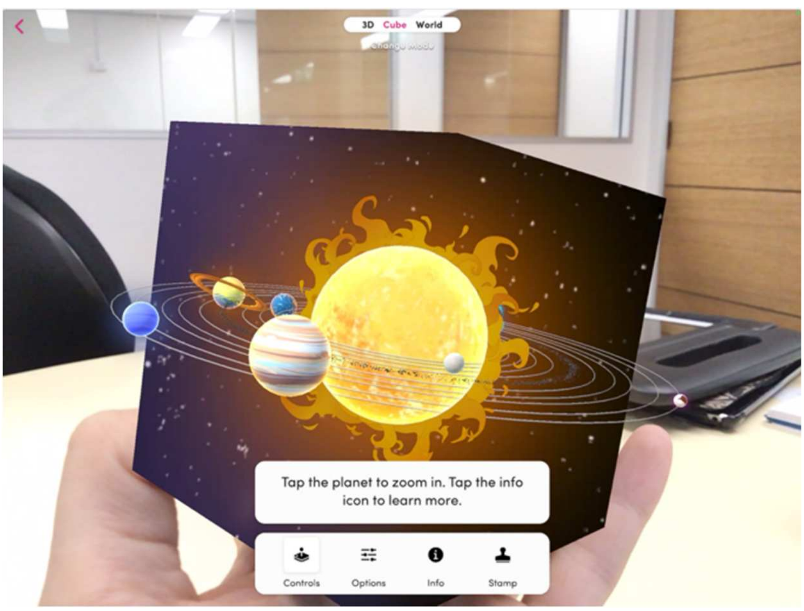


Figure 7. Zach holds the AR Merge cube model of the solar system.

about the planet?" Emma responded: "Yes, sometimes Saturn's rings can be really thin and sometimes really thick". Later, when Emma was presented with information about planetary composition, the researcher asked: "What's inside it?" Emma responded "Iron. It has an iron core". Similarly, when Hunter was asked to summarise the information, he answered: "Venus is the hottest planet in the solar system". Sophia also recollected: "We can't live there because there's carbon and acid in the air". Mason recalled: "Venus is easy to see in the sky, very bright". The efficacious nature of the virtual environment for information recall in our study is supported by research that identified the benefits of immersive VR for enhanced reading comprehension compared to reading captioned video. This benefit was theorised to be associated with immersion and the sense of presence – of being there, interactivity, and because distractions from the real world are blocked from view (Kaplan-Rakowski & Gruber, 2024; Ye & Kaplan-Rakowski, 2024).

The students proficiently retained their newly acquired knowledge, demonstrated after their VR and AR text interactions. Chloe noted that: "There are bigger stars that are far older [than the sun] and are most likely going to explode (supernovae)." Archie called to mind: "When you dig a metre down on Mars, there's actually ice" (Martian polar ice caps), while Emma recalled: "One of the rings on Saturn is called the Phoebe ring." The students in this research demonstrated high enjoyment of this self-directed reading, accurately comprehending and recounting information that was meaningful and aligned to their purpose, and able to be connected to their prior knowledge and experiences.

Resolving cognitive disequilibrium

There were key moments when reading the AR and VR texts that learners experienced a break in the continuous flow of the learning sequence. These moments of uncertainty and questioning are denoted in research as cognitive disequilibrium (Piaget, 1985), an imbalanced state when new knowledge is incongruent with one's existing mental schema (Arguel et al., 2019; Yu et al., 2022). Once resolved, new information becomes part of ones modified schema of the world resulting in learning. For example, Oliver considered the new information presented that Jupiter is a "gas giant" comprised "of the same substances as our Sun, 98% hydrogen and helium". Oliver asked, "Is it not a solid then? So that means you can't physically walk on it, can you?" Similarly, Archie read the written text on the spaceship's dashboard about one of Jupiter's moons, Callisto: "It's outside of Jupiter's main radiation belt". "I don't really understand it." Archie was confused by the terminology "radiation belt", which consists of high-energy charged particles trapped by the planet's magnetic field (NASA, 2024).

Others experienced cognitive disequilibrium about the terminology used, including how the astronomical information in the virtual text was sourced. For example, when using the AR Merge Cube, Zach read the words indicating that the Earth's distance from the Sun was "1 AU" [Astronomical Units], then questioned, "What does "AU" mean?" Later, when reading about each planet using the AR Merge Cube, Zach reflected on information that some planets are gas planets, "With gas planets, how does the gas stay in there? Is it because of something around it?" When reading in VR that Pollux is a star in the Gemini constellation, and challenging the veracity of the virtual source, Chloe asked: "So we don't know … much about the Sun, how do we know about Pollux [which is further away]?"

Recognising his privileged access to distant stars – Pollux, Rigel and VY Canis Majoris – in the simulated voyage, he questioned: "Do you know how they find these stars?" Learners are most likely to experience cognitive disequilibrium when presented with new, complex concepts, coupled with an optimal degree of confusion, which plays a vital role in learning. A well-designed VR or AR textual environment will spark anomalies and novelty that poses a moderate degree of challenge, which if combined with just-in-time feedback or instructional scaffolding can resolve the confusion, leading to positive affect and knowledge acquisition (Yu et al., 2022).

Haptic interactivity to navigate text pathways

To progress through multiple text pathways in both VR and AR applications, students need to physically interact with the text haptically – that is, using touch or human interaction with the external environment using the hand (Minogue & Jones, 2006). The use of touch in AR and VR promotes direct student engagement with the text (Kaplan-Rakowski & Gruber, 2024). Direct haptic engagement with a text cannot be passive, supporting learner agency when navigating a VR or AR text (see Makransky & Petersen, 2021). For example, Noah used the virtual laser to point at the words as he read. He explained, "It helps me know where I'm at". Noah valued being able to haptically direct the reading, commenting that it was easy to pick up the information "because it's just on a board like this, you just press it, and then it goes on to something else". Figure 8 shows Noah's in-game use of the laser pointer (left), and Noah looking down to read the written game text (right).

Others also noted the agency afforded by the haptic interactivity. When asked, "What part of this virtual experience stays with you the most?" Nash replied: "being able to pick up the planets with the controls to move them around". The valuing of the kinaesthetic elements of VR and AR extended to other body movements, as illustrated when Zach jumped out of the virtual spaceship and moved his arms as if floating through the solar system. He said that "climbing" through space was the most memorable part of his VR experience.

Others drew attention to their physical immersion in the virtual text as the most distinctive feature of their experience, such as Riley, who appreciated: "Seeing all the planets to scale compared to me". In addition to travelling to planets that were depicted with relative scales, the game included simulation options to compare the relative scale of planets and stars.

Haptic interactivity was also a key feature to direct and navigate reading using the AR Merge Cube application in which learners corporeally rotated the tangible cube in their hand. For example, Nash was observed rotating the AR Merge Cube to view the labelled components of the Mars Rover (see Figure 9).

Another student, Riley, explained about this 3D model of the Mars Rover (Figure 10): "I can really get a good look at every component". Likewise, as Zach turned the Merge Cube to view the planets, he explained about exploring planetary movement: "It's fun to hold … and play with. You can

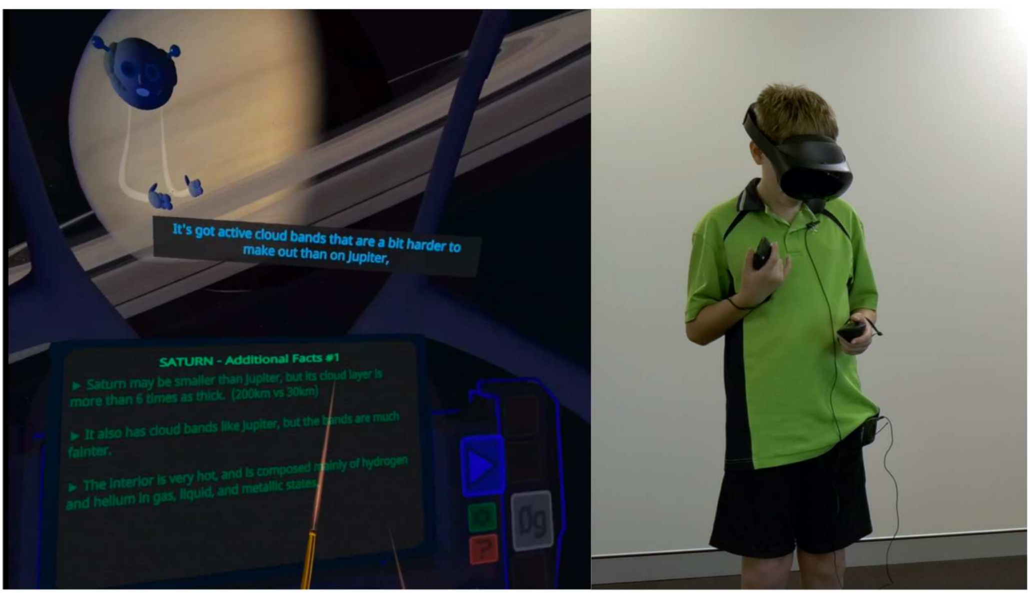


Figure 8. Noah's using haptics to point to the written text.

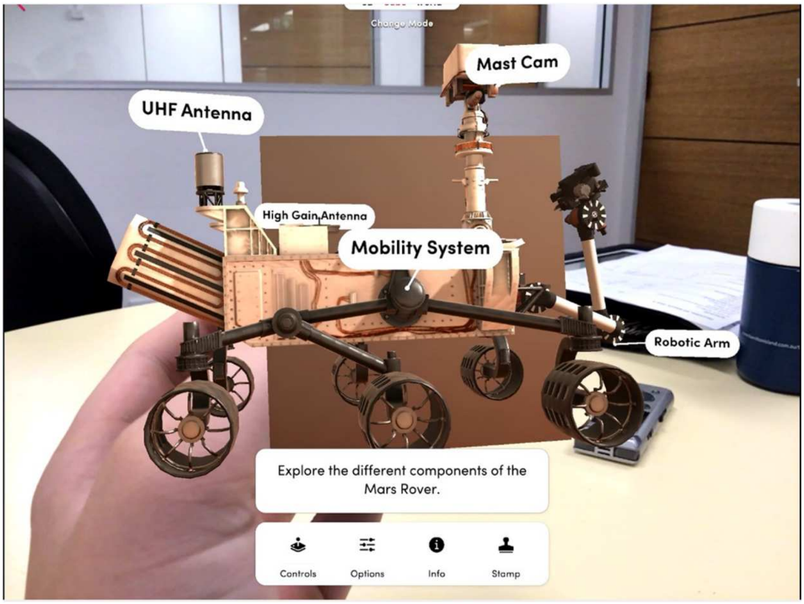


Figure 9. Nash rotates the AR Merge Cube to inspect the Mars Rover.

basically touch it. With a photo, you can't go like that or like this [rotates the cube/3D model]". In each of these instances, the haptic interactivity of the interface supported the students' navigation of the multimodal reading and the simultaneous information exchange between the user and the technology.

Selective attention to filter multimodal information

In the VR and AR multimodal text environments, there were multiple modes and competing attentional cues with varying visual salience, and informational values that are unlike those of a physical book (Jewitt, 2012). In the VR application, the presence of an animated, virtual agent with lifelike

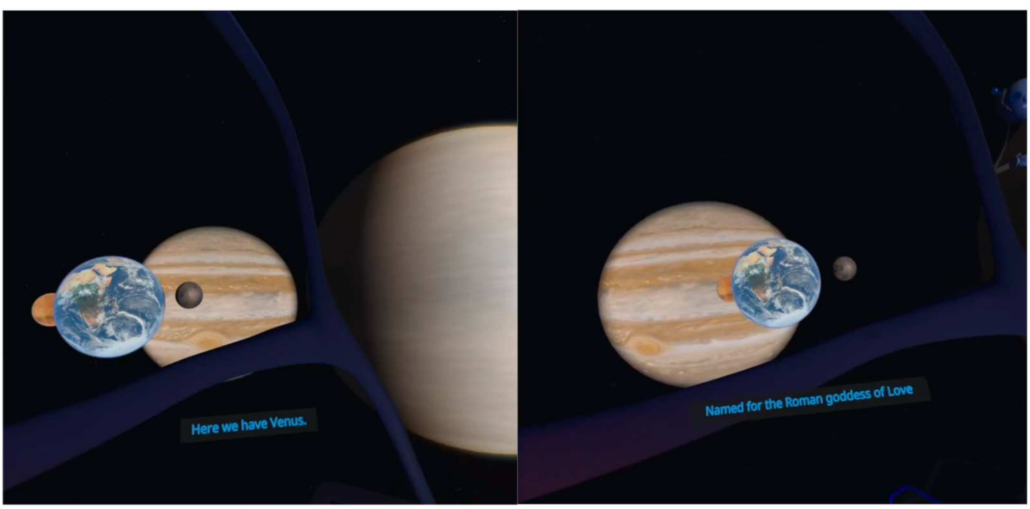


Figure 10. Animation of planetary orbits.

gestures pointing at planets was visually salient, accompanied by audio narration, within a 360-degree, 3D visual representation of the spaceship control centre and immersive solar system. The written text of the virtual agent's narration appeared centred in the users' view. In this multimodal environment, students needed to apply selective attention, or the ability to select or focus on certain information at the exclusion of others, filtering out distracting information (DeGangi, 2017).

The animated virtual agent focused the learning for students like Emma, who reflected that it was "easy" to learn things from the virtual text because the virtual agent "explained things, showing it … in pictures". Yet at times, students chose to filter out the animated virtual agent's speech and action to focus their attention on other visual or written elements. For example, Sophia arrived at Saturn on autopilot. The virtual agent appeared and began describing Saturn's moons, with Saturn depicted in her field of vision. Sophia initially listened to the virtual agent but remarked that she couldn't see any moons. Frustrated, she turned her gaze downward to read the supplementary, detailed text displayed on the spaceship dashboard, which functioned like a footnote in a book. Sophie read aloud: "Saturn has 82 plus known moons", demonstrating her control of the reading and filtering out the virtual agent's commentary on planetary temperature and storms. She redirected her gaze to the depiction of Saturn, still visually searching for the moons and turning her body from side to side, finally satisfied that she had observed the visible moons near Saturn's rings.

Nash was observed tuning out the information presented in the audio and visual presence of the virtual agent, along with the written subtitles, to prioritise watching the animated movement of the planets. When Nash arrived at the planet Venus, even though the virtual agent was positioned centrally in his screen view, gesturing and discussing Venus, Nash first turned to the left to focus on a simulation of Jupiter's orbit (see Figure 10).

Next, Nash turned to the right to focus on the static but dramatic, visually salient depiction of the sun, which filled his field of vision (Figure 11).

Figure 11. Looking to the right, the Sun fills Nash's field of vision.

The virtual agent spoke throughout this time, and the subtitles of the audio followed his head movement, which occurred consistently irrespective of the user's attention. Satisfied that he had visually explored the 3D environment, Nash returned his gaze to the centre to the animated virtual agent and the planet Venus (Figure 12).

To avoid splitting his attention across multiple modes, Nash asked, "How do I turn the sound off? It would be easier if I could read this and not have to listen". Turning off the virtual agent removed the audio as well as the sub-title text from the screen and allowed the student to focus his attention selectively on the detailed written information. The student opted for more information using the "i" button on the dashboard, searching for more complex information by clicking on the prompt "Jupiter – Additional Facts".

In a similar way, Noah selectively attended to the detailed information contained on the spaceship dashboard, while filtering out other distracting information from the virtual agent animations, audio, and visual representations. He read aloud: "This one says [of Rigel] the sun is 860 light years [away], age eight million". Likewise, Emma, focusing on the dashboard text, announced: "Oh, Saturn's rings are made of water – ice!" The use of selective attention was a useful mechanism applied by the students to process selected content of importance and interest, and for task-relevant information gathering. This ability was essential in the multimodal reading environment where textual pathways for attention were omnidirectional, and where the goal of acquiring in-depth knowledge about phenomena could be pursued without distraction (Cowan et al., 2005).

Through focused attention on the visual and spatial elements of the three-dimensional text environment, the students were supported in the development of new mental models to comprehend the relative scale of phenomena. For example, while Oliver had read about the planetary sizes in books, being immersed in a simulation of the solar system enabled him to intuitively grasp the relative enormity of the sun: "There's the sun – the sun is so big compared to all the other

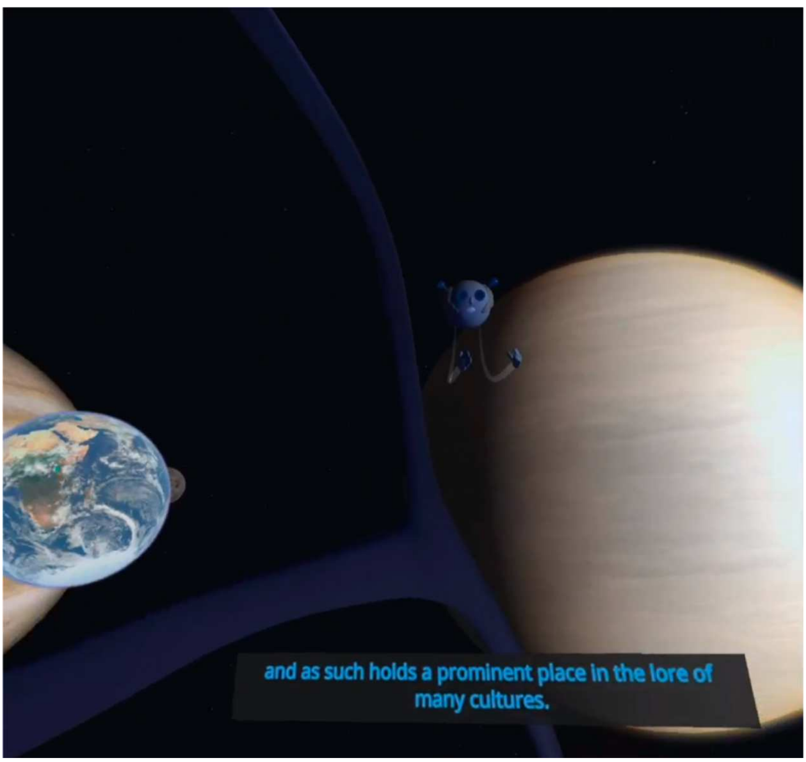


Figure 12. Nash's centred view at the planet Venus and the animated virtual agent.

Figure 13. Joanna's and Michael's teacher interview themes.

planets!" In a similar way, when asked about his most memorable learning from the VR experience, Archie noted the scale of the heavenly bodies: "How do I explain this? Like, how much you don't realise how big the Earth is, but then compared to the Sun, and then compared to that huge star, Pollux. It's so cool". The increased size of the visuals through an HMD and the heightened depth perception in immersive 3D environments were powerful affordances of VR, enabling the students to focus selectively on spatial relations.

Teacher perspectives of VR and VR for literacy

Reflexive thematic analysis of the teacher interview data identified that Joanna was focused on the benefits of VR and AR for student motivation and learning engagement, with key themes emerging as "learning", "motivation", "information", "create", "think", and "engage" (see Figure 3, left). She explained: "Quite a few of the students that are normally very quiet, and it's hard to get them to engage in the lesson. They've engaged more, and they've produced more. They have had better outcomes today than usual". Michael noticed the students' positive affect: "Emma had low energy going into the VR, and then afterwards she was pretty excited" having "discovered" new knowledge about the planets. Michael also reflected on how teachers can modify the curriculum to incorporate VR and AR for students' information gathering (see Figure 13, right). Integrating these experiences across the content areas, as well as a focus on genre in the English curriculum: "students knew they were going to create their story using augmented reality. So it connected the learning".

Joanna's students included some who struggled to engage in reading books, and for these students, "quite often, seeing one-dimensional words [on a page] doesn't really capture their imagination". She observed that with reading in both VR and AR, "They get taken into a different dimension" and gain a "deeper connection with learning, with lots of benefits: engagement, … outcomes … enjoyment, and … motivation". Teachers' observations of student engagement are consistent with results reported by Kaplan-Rakowski and Gruber (2024), who found that students experienced immersive VR reading as engaging and motivating.

Discussion

The current study demonstrated how reading in AR, and an immersive VR multimodal environment, can support learners in a variety of ways. It was identified that the ability to place students into an entirely virtual world enabled them to recall previously learned material and apply it to the current environment. Rather than feeling like they were purely identifying new information, as common from a textbook or traditional resource, learners increasingly referred back to past knowledge to explain the reading content in which they were immersed. These connections between the new and known can be of great benefit to overall learning (Dong et al., 2020; Kalantzis & Cope, 2005).

The ease with which students were able to recall learned content after the reading experience was also of note. This could potentially lead to enhanced longer-term retention, especially when the virtual world has been structured in a way that the student experiences the world by "doing", rather than simply watching or listening (Moro et al., 2024). In particular, performing actions within a virtual world, even as simple as turning a page of a simulated book, represents real-world skills. This merging of the real and virtual environment is important, as there are growing concerns that certain kinds of screen use, such as passive television viewing, and excessive screen use, may impact young people's abilities to perform particular real-world functions (Baron, 2015).

It was not surprising to find benefits from a virtual environment towards the identification and rectification of cognitive disequilibrium. Not only are students presented with new content, but in some cases, an entirely new and unfamiliar virtual world of text to explore (Yu et al., 2022). While students were quite knowledgeable about the names and locations of planets when it was synthesised in virtual space through multiple modes, aspects such as the relative scale of the solar system was enlivened. The challenge of previously learned concepts was identified in a number of cases, such as the learner not realising that humans would be unable to walk on Jupiter as a solid planet. Virtual presentations of this nature may be of particular benefit when learning content that is highly reliant upon 3D representations, such as space or human body structures (Moro et al., 2021). Learners experience cognitive disequilibrium when presented with complex concepts that present an optimal degree of confusion. Teachers and expert peers can provide timely feedback to support students when they ask questions about a VR or AR text that has sparked anomalies, providing a supportive instructional context to optimise these teachable moments (Yu et al., 2022).

While there have been concerns that a virtual environment can be distracting for some readers (Asish et al., 2022), the ability of students in the present study to readily recall new content, demonstrates that well-designed XR applications can successfully sustain the learner's attention. In fact, students demonstrated a clear ability to selectively focus their attention within the VR and AR multimodal text environments in a way that filtered important information. Previous research has shown how VR can be used to enhance motivation and a sense of presence when reading without compromising cognitive load (Kaplan-Rakowski & Gruber, 2024), while incorporating VR into reading activities offers can enhance reading fluency, support motivation for reading, and transform reading into a habit. Importantly, beyond the physical book, reading is increasingly introduced to primary students through a variety of modes or digital platforms (Apps et al., 2023). As such, while quite new, virtual, and augmented reality lessons might not be perceived as "futuristic" by modern students, who have grown up with far more integrated technology than other generations (Dezuanni, 2018).

Teachers should play-test and pre-assess VR and AR applications to determine the age-appropriateness, value, game mechanics, task time, and alignment with the curriculum outcomes and assessments. For example, the XR applications in this research were purposefully selected for students to gather relevant information about space travel for their inquiry learning projects. Multiplayer games should be excluded for e-safety for children, gameplay can be streamed to an interactive whiteboard for collaboration and support from teachers and peer experts, and devices should be used for a controlled duration (Australian Government, 2023). Contemporary VR devices are plug-and-play, hosting enhanced integrations into operating systems, and a simpler interface than earlier integrations. This, along with an increased teacher awareness of XR technologies (Walstra et al., 2024), has minimised earlier inhibitory factors, with strategies for teaching with VR and AR readily available across disciplines (Lin et al., 2024). The increased accessibility of virtual and augmented reality integrations and their identified benefits suggest that education is poised for XR technologies to become increasingly integrated across classrooms globally.

Conclusion

Everyday digital reading is not going away, rather, it is becoming ubiquitous with the widespread use of mobile digital devices amidst global, societal, and technological changes. To date, many studies fail to clearly delineate, conceptualise, and identify the metacognitive processes and agentive capabilities involved in reading across different kinds of digital devices, particularly VR, and to a lesser extent, AR (Fan et al., 2020; Mills et al., 2022; Singer & Alexander, 2017). There is some urgency in recalibrating what it means to read and navigate information in the context of expanded forms of immersive, multidirectional, multimodal texts (VR), and with haptically interactive 3D augmented models (in AR), because not all screen reading is the same. Similarly, while much educational technology has focused on passive viewing, rather than actively doing (Moro et al., 2024), most VR and AR text environments necessitate that learners apply active, metacognitive reading, while haptically mediating the navigation of 3D models and environments selected from multiple alternate pathways to drive the reading onwards (Mills et al., 2023).

This research is timely given that students today need advanced skills to navigate, recall, and apply metacognitive reading of virtual and augmented reality multimodal texts, with unique combinations of audio narration, words, 3D imagery, and animations. VR and AR texts often lack the conventional material anchors that book offer, such as pages to turn, which aid memory, while some poorly designed apps may include distracting functions and hotspots that can disrupt the reading (Falloon, 2023; Mills et al., 2023). Text navigation in VR and AR contexts is markedly different from the top-down, left-to-right, front-to-back linearity of conventional books (Golan et al., 2018). Teachers need broadened repertoires of technology-related skills and knowledge to support students with AR- and VR-based multimodal reading across different curriculum areas while making informed pedagogical decisions to determine how applications are integrated authentically and adapted for use within the curriculum. Given that digital reading has increased dominance over paper reading in many societal contexts, and given the mixed reading outcomes for learners across diverse digital media formats, applications, age groups, and cultural contexts (Delgado et al., 2018), it is vital to continue to expand XR research to understand how students of all ages navigate the complexities of VR and AR reading environments.

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References

Apps, T., Beckman, K., & Howard, S. K. (2023). Valuable data? Using walkthrough methods to understand the impact of digital Reading platforms in Australian primary schools. *Learning, Media and Technology*, *48*(2), 294–309. https://doi.org/10.1080/17439884.2022.2160458

Arguel, A. A., Lockyer, L., Kennedy, G., Lodge, J. M., & Pachman, M. (2019). Seeking optimal confusion: A review on epistemic emotion management in interactive digital learning environments. *Interactive Learning Environments*, *27*(2), 200–210. https://doi.org/10.1080/10494820.2018.1457544

Asish, S. M., Kulshreshth, A. K., & Borst, C. W. (2022). Detecting distracted students in educational VR environments using machine learning on Eye gaze data. *Computers & Graphics*, *109*, 75–78. https://doi.org/10.1016/j.cag.2022.10.007

Australian Bureau of Statistics (ABS). (2021). Census QuickStats search. Australian Bureau of Statistics. https://abs.gov.au/census/find-census-data/quickstats/2021/SAL32117

Australian Curriculum, Assessment and Reporting Authority (ACARA). (2023). "F-10 Curriculum." https://v9.australiancurriculum.edu.au/

Australian Government. (2023). *Virtual reality (VR). eSafety commissioner*.

Australian Research Council. (2018). *National Statement on Ethical Conduct in Human Research*. National Health and Medical Research Council. https://www.nhmrc.gov.au/research-policy/ethics/national-statement-ethical-conduct-human-research

Baron, N. S. (2015). *Words onscreen: The fate of Reading in a digital world*. Oxford University Press.

Blevins, B. (2018). Teaching digital literacy composing concepts: Focusing on the layers of augmented reality in an Era of changing technology. *Computers & Composition/Computers and Composition*, *50*, 21–38. https://doi.org/10.1016/j.compcom.2018.07.003

Byrne, D. (2022). A worked example of braun and clarke's approach to reflexive thematic analysis. *Quality & Quantity*, *56*(3), 1391–1412. https://doi.org/10.1007/s11135-021-01182-y

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. A. (2005). On the capacity of attention: Its estimation and Its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*(1), 42–100. https://doi.org/10.1016/j.cogpsych.2004.12.001

DeGangi, Georgia A. 2017. *Pediatric disorders of regulation in affect and behavior.* (Second Edition). Academic Press.

Delgado, P., Vargas, C., Ackerman, R., & Salmerón, L. (2018). Don't throw away your printed books: A meta-analysis on the effects of Reading media on Reading comprehension. *Educational Research Review*, *25*, 23–38. https://doi.org/10.1016/j.edurev.2018.09.003

Dezuanni, M. (2018). Minecraft and children's digital making: Implications for media literacy education. *Learning, Media and Technology*, *43*(3), 236–249. https://doi.org/10.1080/17439884.2018.1472607

DiCicco-Bloom, B., & Crabtree, B. F. (2006). The qualitative research interview. *Medical Education*, *40*(4), 314–321. https://doi.org/10.1111/j.1365-2929.2006.02418.x

Dong, A., Jong, M. S.-Y., & King, R. B. (2020). How does prior knowledge influence learning engagement? The mediating roles of cognitive load and help-seeking. *Frontiers in Psychology*, *11*, 591203-1–10. https://doi.org/10.3389/fpsyg.2020.591203

Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology*, *18*(1), 7–22. https://doi.org/10.1007/s10956-008-9119-1

Ebadi, S., & Ashrafabadi, F. (2022). An exploration into the impact of augmented reality on EFL learners' Reading comprehension. *Education and Information Technologies*, *27*(7), 9745–9765. https://doi.org/10.1007/s10639-022-11021-8

Falloon, G. (2023). Twelve years of iPads and apps in schools. *Frontiers in Education*, *8*, 1122522. https://doi.org/10.3389/feduc.2023.1122522

Fan, M., Antle, A. N., & Warren, J. L. (2020). Augmented reality for early language learning: A systematic review of augmented reality application design, instructional strategies, and evaluation outcomes. *Journal of Educational Computing Research*, *58*(6), 1059–1100. https://doi.org/10.1177/0735633120927489

Friend, L., & Mills, K. (2022). Analyzing virtual reality data. In F. Serafini (Ed.), *In beyond the visual: An introduction to researching multimodal phenomena* (pp. 197–200). Teachers' College Press.
Garcez, A., Duarte, R., & Eisenberg, Z. (2011). Production and analysis of video recordings in qualitative research. *Educacao e Pesquisa*, *37*(2), 249–260. https://doi.org/10.1590/S1517-97022011000200003
Golan, D. D., Barzillai, M., & Katzir, T. (2018). The effect of presentation mode on children's Reading. *Computers & Education*, *12*, 346–358. https://doi.org/10.1016/j.compedu.2018.08.001
Hevey, D. (2020). Think-aloud methods. In N. J. Salkind (Ed.), *In encyclopedia of research design* (pp. 1505–1506). SAGE.
Ho, L., & Limpaecher, A. (2023, April 6). "What Is Consensus Coding and Split Coding in Qualitative Research?" Delve. https://delvetool.com/blog/consensus-coding-split-coding
Jewitt, C. (2012). *Technology, literacy, learning: A multimodal approach*. Routledge.
Kalantzis, M., & Cope, B. (2005). *Learning by design*. Victorian Schools Innovation Commission and Common Ground Publishing.
Kaplan-Rakowski, R., & Gruber, A. (2024). An experimental study on Reading in high-immersion virtual reality. *British Journal of Educational Technology*, *55*(2), 541–559. https://doi.org/10.1111/bjet.13392
Kieffer, M. J., Vukovic, R. K., & Berry, D. (2013). Roles of attention shifting and inhibitory control in 4th grade Reading. *Reading Research Quarterly*, *48*(4), 333–348. https://doi.org/10.1002/rrq.54
Lin, X., Li, R., Chen, Z., & Xiong, J. (2024). Design strategies for VR science and education games from an embodied cognition perspective: A literature-based meta-analysis. *Frontiers in Psychology*, *14*, 1292110. https://doi.org/10.3389/fpsyg.2023.1292110
Makransky, G., & Petersen, G. B. (2021). The cognitive affective model of immersive learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality. *Educational Psychology Review*, *33*(3), 937–958. https://doi.org/10.1007/s10648-020-09586-2
Mills, K. A. (2019). *Big data for qualitative research* (1st ed.). Routledge.
Mills, K. A. (2022). Potentials and challenges of extended reality technologies for language learning. *Anglistik*, *33*(1), 147–163. https://doi.org/10.33675/ANGL/2022/1/13
Mills, K. A., & Brown, A. (2021). Immersive virtual reality (VR) for digital media making: Transmediation is Key. *Learning, Media and Technology*, *47*(2), 179–200. https://doi.org/10.1080/17439884.2021.1952428
Mills, K. A., & Brown, A. (2023). Smart glasses for 3D multimodal composition. *Learning, Media and Technology*, 1–22. https://doi.org/10.1080/17439884.2023.2207142
Mills, K. A., Brown, A., & Funnell, P. (2024). Virtual reality games for 3D multimodal designing and knowledge across the curriculum. *The Australian Educational Researcher*, 1–31. https://doi.org/10.1007/s13384-024-00695-3
Mills, K. A., Scholes, L., & Brown, A. (2022). Virtual reality and embodiment in multimodal meaning making. *Written Communication*, *39*(3), 335–369. https://doi.org/10.1177/07410883221083517
Mills, K. A., Unsworth, L., & Scholes, L. (2023). *Literacy for digital futures: Mind, body, text*. Routledge.
Minogue, J., & Jones, M. G. (2006). Haptics in education: Exploring an untapped sensory modality. *Review of Educational Research*, *76*(3), 317–348. https://doi.org/10.3102/00346543076003317
Moro, C., Bhagat, K., Veer, V., Varma, G., Das, A., & Birt, J. (2023). Indian and Australian university students' acceptance of using accessible, Web-based, and smartphone-delivered augmented reality. *Journal of University Teaching & Learning Practice*, *20*(6), 1–23. https://doi.org/10.53761/1.20.6.14
Moro, C., Birt, J., Stromberga, Z., Phelps, C., Clark, J., Glasziou, P., & Scott, A. (2021). Virtual and augmented reality enhancements to medical and science student physiology and anatomy test performance: A systematic review and meta-analysis. *Anatomical Sciences Education*, *14*(3), 368–376. https://doi.org/10.1002/ase.2049
Moro, C., Mills, K. A., & Phelps, C. (2024). The CRAFTS learning framework: Equipping learners to create relevant, accessible, Fun, tailored and scholarly activities in higher education. *Interactive Learning Environments*, *32*(10), 7230–7241. https://doi.org/10.1080/10494820.2024.2308100.
NASA. (2024). "Jupiter Facts." Effective August 20. https://science.nasa.gov/jupiter/jupiter-facts/
Ok, M. W., Haggerty, N., & Whaley, A. (2021). Effects of video modeling using an augmented reality iPad application on phonics performance of students who struggle with Reading. *Reading & Writing Quarterly*, *37*(2), 101–116. https://doi.org/10.1080/10573569.2020.1723152
Open Broadcaster Software (OBS). (2024). Open Broadcaster Software v28.0.1. https://obsproject.com/
Paquette, K., Laverick, D., & Sibert, S. (2020). Virtual reality experiences as an instructional strategy for promoting comprehension. *Reading Improvement*, *57*(4), 173–179.
Piaget, J. (1985). *The equilibration of cognitive structures*. University of Chicago.
Singer, L. M., & Alexander, P. A. (2017). Reading on paper and digitally: What the past decades of empirical research reveal. *Review of Educational Research*, *87*(6), 1007–1041. https://doi.org/10.3102/0034654317722961
Southgate, E., Blackmore, K., Pieschl, S., Grimes, S., McGuire, J., & Smithers, K. (2019). *Artificial intelligence and emerging technologies in schools: A research report*. University of Newcastle.
Veer, V., Phelps, C., & Moro, C. (2002). Incorporating mixed reality for knowledge retention: A randomized controlled trial. *Medical Science Education*, *32*(6), 1579–1586. https://doi.org/10.1007/s40670-022-01635-5

Walstra, K. A., Cronje, J., & Vandeyar, T. (2024). A review of virtual reality from primary school teachers' perspectives. *Electronic Journal of e-Learning*, *22*(3), 1–11. https://doi.org/10.34190/ejel.21.4.3060

Ye, Y., & Kaplan-Rakowski, R. (2024). An exploratory study on practising listening comprehension skills in high-immersion VR. *British Journal of Ed Tech*, *55*(4), 1651–1672. https://doi.org/10.1111/bjet.13481

Yu, J., Denham, A. R., & Searight, E. (2022). A systematic review of AR game-based learning in STEM education. *Educational Technology Research and Development*, *70*(4), 1169–1194. https://doi.org/10.1007/s11423-022-10122-y