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Cognitive Overload or Motivational Anchor? Evaluating AI-Integrated 5E Science Instruction in Grade 7 and 8 Classrooms via a Quasi-Experimental Crossover Design

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Abstract: Concerns regarding decreased attention spans associated with modern digital media consumption challenge traditional direct teaching. This study evaluates a multimedia-integrated teaching method on Grade 7 and 8 students at Miza Educational Institute in Hulhumalé, Maldives. Using a quasi-experimental crossover design, 115 experimental observations were gathered from 91 unique students, with participants crossing over to experience both the experimental and control conditions. The intervention included an AI-generated video hook, direct instruction, a summary video, and an immediate retrieval quiz. Analyzed via linear mixed-effects modeling (LMM), results revealed a profound developmental interaction effect driven by intrinsic cognitive load. For Grade 7 (low intrinsic load), multimedia integration acted as an effective motivational anchor, yielding a statistically significant improvement in immediate retrieval scores. Conversely, for Grade 8 (high intrinsic load), the data suggests that the intersection of high element interactivity and the transient information effect likely induced cognitive overload, acting as the primary explanatory hypothesis for the performance drop. In this context, the multimedia appeared to act as seductive details, resulting in significantly higher immediate retrieval scores for the traditional direct instruction cohort. AI-generated multimedia must be rigorously calibrated to learners' cognitive maturity and the syllabus's intrinsic difficulty.

Keywords: Educational Technology, Science Education, Middle School Education, Adolescent Learning, 5E Instructional Model

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1. Introduction

Smartphone usage is embedded in every aspect of modern daily life, including communication, information access, and entertainment. The last decade has witnessed a substantial rise in smartphone utilization among children and adolescents (Sohn et al., 2019). The ubiquitous nature of smartphones has raised significant concerns regarding excessive usage and addiction, making its impact on cognitive and psychological well-being a critical focus of contemporary research(Amalakanti et al., 2024). Adolescents represent a particularly vulnerable demographic for smartphone addiction, often exhibiting a profound psychological attachment wherein the device is perceived as an extension of their own identity (Cha & Seo, 2018). Short-form videos have quickly become a staple of adolescents' daily routines, but excessive consumption presents significant challenges in educational contexts. Addiction to these platforms is consistently linked to increased anxiety, chronic procrastination, and overall declines in academic achievement. (Xiong et al., 2026). Furthermore, literature suggests that extensive internet exposure may influence cognitive processing patterns and underlying neural networks, presenting new challenges for formal education and exam preparation (Firth et al., 2019). Furthermore, Ward et al. (2017) theorized a cognitive "brain drain" effect, where the mere physical presence of a smartphone may reduce an individual's available working memory capacity and fluid intelligence. Crucially, this depletion of cognitive resources occurs subconsciously, even in the absence of active distractions or conscious thoughts regarding the device. According to Mona et al. (2026), short-video addiction (SVA) is associated with significant cognitive and behavioral deficits, though self-control serves as a critical protective factor against vulnerabilities like impulsivity and boredom.

Nadeem et al. (2020) suggest that traditional didactic teaching methods are no longer inclusive, as Generation Z expects instructional novelty. Furthermore, some educators observe that modern students frequently struggle with sustained focus; concerns exist that chronic digital media consumption may contribute to shortened attention spans, potentially reducing the efficacy of traditional chalk-and-talk methods (Kaushik et al., 2024). This pedagogical crisis is particularly acute in science education, where students increasingly struggle to achieve deep conceptual understanding (Solikah, 2026). This creates a direct conflict with modern educational mandates. Contemporary curricula ranging from the Maldives National Curriculum Framework (National Institute of Education, 2015) to broader international benchmarks (Department for Education, 2013; Ministry of Human Resource Development, 2020) universally demand higher-order cognitive capacities, such as critical thinking and complex problem-solving. Fulfilling these rigorous goals in Maldivian classrooms can be hindered when students experience cognitive fatigue, making it difficult for them to engage in the deep, analytical inquiry that science education requires.

It is evident that the usage of technology among students acts as a bottleneck to achieving contemporary educational goals; simultaneously, however, it serves as a powerful tool to make the teaching and learning process both efficient and effective. Educators should understand this paradox and be careful enough to align teaching methodologies to match the cognitive realities of Generation Z (Mihelič & Culiberg, 2026). Rather than discarding the 5E instructional model (Bybee et al., 2006), which provides a robust foundation to consolidate students' knowledge and skills, educators can adapt and optimize it to contemporary cognitive and technological realities. Through the strategic incorporation of digital media, traditional educational frameworks can be recalibrated to effectively serve the modern educational goals (Mishra & Koehler, 2006). The aim of this study is to investigate the efficacy of adapting the 5E Instructional Model through video-integrated direct instruction. By utilizing short-video summary hooks during the initial phases of instruction, this research seeks to determine if such targeted multimedia interventions can successfully capture fractured attention and enhance overall science comprehension among modern adolescent learners.

1.1. Background to Study

In the Maldives, the secondary education framework follows a strict pedagogical progression; students build their foundational knowledge under the Maldives National Syllabus through Grade 8 before transitioning to the Cambridge International General

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Certificate of Secondary Education (IGCSE) and the Pearson Edexcel International Advanced Level (IAL) in their upper secondary years (National Institute of Education, 2015; Ministry of Education, 2019; Department of Public Examinations, n.d.) (see Table 1).

Table 1. Progression of Science Education Structure and Subjects across School Phases and Key Stages in Maldives (National Institute of Education, 2015).

Phase	Key Stage	Grades	Science Education Structure & Subjects
Foundation	—	LKG, UKG	Environment, Science & Technology (Integrated approach across learning areas)
Primary	Key Stage 1	Grades 1, 2 & 3	Science (Core subject)
Primary	Key Stage 2	Grades 4, 5 & 6	Science (Core subject)
Lower Secondary	Key Stage 3	Grades 7 & 8	Science (Core subject including Physics, Environmental Science, Chemistry & Biology)
Lower Secondary	Key Stage 4	Grades 9 & 10	**Electives** (Must select at least one subject from the KLA Environment, Science & Technology out of 4 chosen electives): • Physics • Chemistry • Biology • Marine Sci (Marine Science) • Environ. Sci (Environmental Science) • Combined Science
Higher Secondary	Key Stage 5	Grades 11 & 12	**Electives** (Choose any 3 subjects): •Physics • Chemistry • Biology • Marine Sci (Marine Science)

Miza Educational Institute in Hulhumalé supports this robust academic system by providing small group classes for students from both local and international schools and preparing them for the school and national and international examinations. The institute's teaching objectives align with the national educational goals. It starts with the Maldives National Syllabus for Grades 1 through 8 then moves to the Cambridge IGCSE for Grades 9 and 10 and ends with the Pearson Edexcel IAL for Grades 11 and 12 . (National Institute of Education, 2015).

In this educational context, this study looks specifically at students in Grades 7 and 8 learning science according to the Maldives National Syllabus. This stage of education requires a cognitive shift. Students must transition from passive observation to abstract thinking and active inquiry to grasp complex concepts (National Institute of Education, 2015). To learn these basic science ideas, students need to stay focused and think for a long time. For contemporary adolescents, whose attention is frequently fragmented by digital media (Firth et al., 2019), sustaining the focus required to process and retain scientific material presents a significant pedagogical challenge (Kaushik et al., 2024).

To address this pedagogical dilemma, instructional strategies may need to account for the digital consumption patterns of the contemporary "internet-savvy generation" (Jacobs et al., 2025). Delivery methods can be modified to accommodate potential fluctuations in middle school students' attention spans. The proposed instructional method is not a complete abandonment of the traditional teaching methods but rather an optimized version of the 5E instructional framework (Bybee et al., 2006) reinforced by a short video engagement hook and immediate retrieval practice.

1.2. Statement of the Problem

According to the National Curriculum Framework of Maldives (National Institute of Education, 2015) studying science equips students to become critical thinkers who appreciate scientific methodologies and act as informed decision-makers. This foundational knowledge empowers them to actively contribute to sustainable development and navigate complex ethical, moral, and environmental issues within their

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communities. Educators frequently struggle to fulfill these pedagogical goals due to evolving media consumption habits among Generation Z, potential challenges with sustained attention, and the varying efficacy of traditional didactic methods (Jacobs et al., 2025). This results in poor memory retention and a failure to grasp foundational science concepts, creating substantial barriers to achieving national educational goals (Wei et al., 2026).

While the 5E Instructional Model provides a proven framework for scientific inquiry, its traditional application often lacks the targeted multimedia pacing that may be necessary to capture and sustain student engagement in modern digital contexts. Furthermore, there is a limited number of studies related to optimizing this model for the evolving media habits of modern adolescents. This study aims to fill the research gap by adjusting the 5E Instructional Model to better engage contemporary learners using a short video engagement hook, short video summary, and immediate retrieval practice.

By aligning this model with the cognitive habits of Generation Z and Alpha learners, this study further investigates the potential to efficiently achieve national science education goals in the Maldives.

1.3. Research Objectives

1.3.1. General Objective

The primary objective of this study is to critically evaluate the impact of a structured multimedia instructional sequence on the immediate post-lesson performance and engagement of Grade 7 and 8 science students.

This sequence integrates cognitively stimulating multimedia hooks and visual summaries around a core of direct instruction, which is subsequently followed by immediate retrieval practice.

1.3.2. Specific Objectives

1. To systematically compare the immediate post-lesson quiz marks between an experimental group and a control group to determine academic efficacy.
2. To investigate the pedagogical effectiveness of intentional content sequencing by isolating visually rich, AI-generated multimedia at the boundaries of a lesson to prevent extraneous cognitive load.

1.4. Hypotheses / Research Questions

Null Hypothesis (H_0): There is no statistically significant difference in immediate post-lesson quiz scores between middle school science students taught using the structured video-integrated instructional model and those taught using traditional direct teaching.

Alternative Hypothesis (H_1): There is a statistically significant difference in immediate post-lesson quiz scores, favouring students taught using the structured video-integrated instructional model compared to traditional direct teaching.

2. Literature Review

2.1. Theoretical Framework

The core principle of Cognitive Load Theory is that human working memory possesses a strictly finite capacity for processing simultaneous information. When learners face unnecessary mental demands such as ineffective instructional design or environmental distractions extraneous cognitive load increases, ultimately obstructing comprehension and knowledge transfer.

Conversely, processing intrinsically complex scientific concepts requires productive mental effort, known as germane load.

Therefore, to optimize learning, instruction must be carefully designed to minimize irrelevant cognitive strain while maximizing the mental resources dedicated to meaningful processing, ensuring the total demand never exceeds the learner's available cognitive capacity(Sweller et al., 2019). (see Figure 1).

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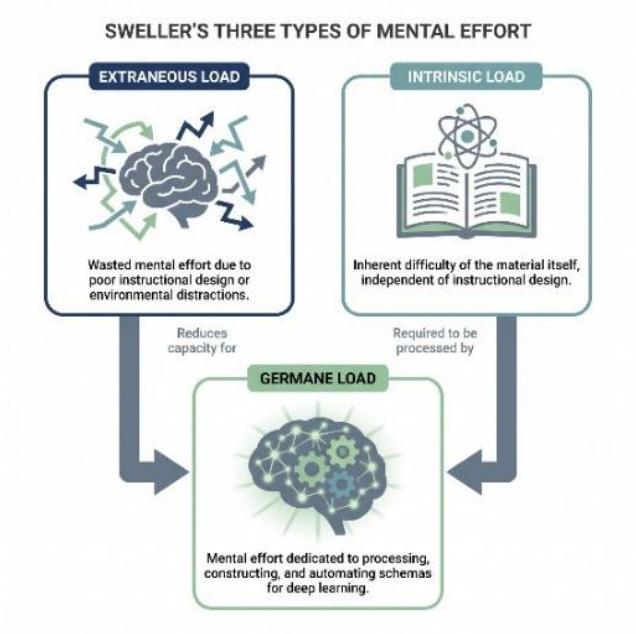


Figure 1. The three types of mental efforts (Sweller et al., 2019)

Literature suggests that excessive use of digital devices may strain the baseline working memory capacity of some middle schoolers. Empirical research identifies excessive short-video consumption as a potential contributing factor to this cognitive fatigue (Li et al., 2026).

To understand the necessity of this 'working memory' in learning, it is essential to critically examine Evolutionary Educational Psychology (Geary, 2008) (see Figures 2 and 3). According to Geary (2008), humans possess 'biologically primary' cognitive domains that evolved to automatically and effortlessly process information routinely encountered throughout our evolutionary history.

However, the ability to learn evolutionarily novel information (biologically secondary) requires learners to actively inhibit these automatic folk systems and instead engage in controlled, effortful problem-solving (Geary, 2008). Furthermore, Geary (2008) and Sweller (2008) explain that these processing skills demand higher cognitive load or working memory.

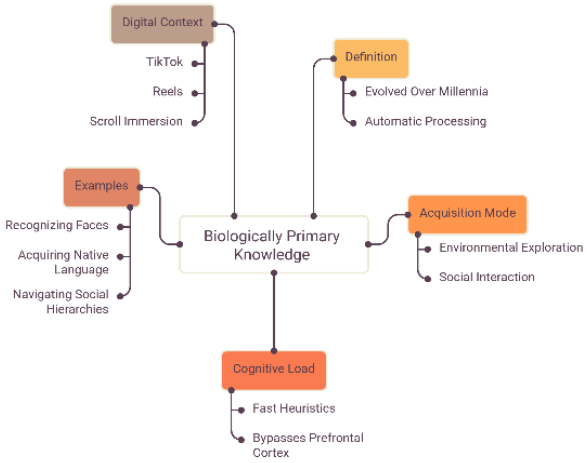


Figure 2. Mind map illustrating the cognitive architecture, evolutionary characteristics, and modern digital context of Biologically Primary Knowledge (Adapted from Geary, 2008). Theoretical Framework: This visualization maps out information processed automatically through evolutionary adaptation and modern digital platforms, contrasting with biologically secondary knowledge.

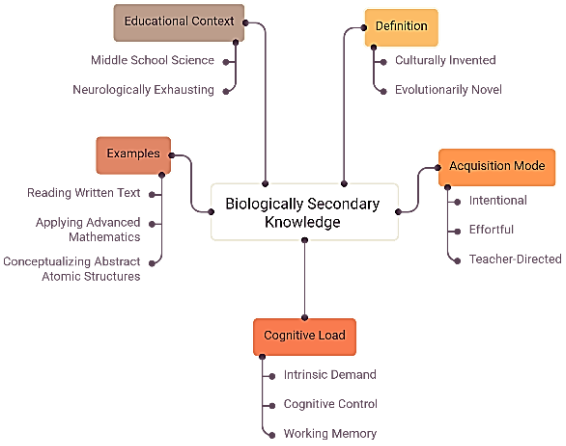


Figure 3. Mind map illustrating the cognitive architecture, acquisition mode, and educational context of Biologically Secondary Knowledge (Adapted from Geary, 2008). Theoretical Framework: This visualization maps out information that is culturally invented, evolutionary novel, and intentionally acquired, highlighting the high cognitive load and working memory demands characteristic of middle school science instruction.

The middle school science framework outlined in the Maldives National Syllabus (National Institute of Education, 2015) consists entirely of complex, biologically secondary knowledge across biology, chemistry, and physics. Concepts such as atomic structure, Hooke's Law, the conservation of energy, and cellular transport represent abstract, evolutionary

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novel information. The biological bottleneck in achieving these curricular demands is grounded in developmental neuroscience. As Blakemore and Choudhury (2006) highlight, core executive functions such as inhibitory control, processing speed, working memory, and decision-making are not fully mature in middle schoolers; rather, they continue to undergo significant development throughout adolescence. Luna et al. (2010) further elaborate on this neurological burden, noting that the prefrontal cortex networks responsible for cognitive control remain highly vulnerable and transitional during this age. Consequently, forcing Grade 7 and 8 students to process highly complex, secondary science concepts places an immense demand on their still-developing working memory, rendering the process inherently stressful and neurologically exhausting. While this represents the natural developmental context of adolescent working memory, these inherent limitations are potentially exacerbated by broader generational trends of excessive digital media consumption and short-form video habits (Firth et al., 2019; Mona et al., 2026).

While many contemporary adolescents face challenges maintaining sustained focus during abstract science lessons, Alruwaili (2025) notes that they often find it difficult to disengage from short video platforms such as TikTok, Instagram Reels, and YouTube Shorts. This cognitive paradox can be addressed by Geary's (2008) Evolutionary Educational Psychology. These platforms focus entirely on delivering high-intensity, biologically primary cues, such as dynamic movement, bright colors, human faces, and simple social narratives. Because the human brain evolved to process these specific environmental cues automatically, consuming this media bypasses the prefrontal cortex's executive functions. Consequently, it triggers a state of "scroll immersion," a form of habitual, low-intention engagement where users process information with minimal cognitive effort and lose temporal awareness (Alruwaili, 2025).

According to Mayer's (2021) Cognitive Theory of Multimedia Learning (CTML), the human brain processes visual imagery and verbal/auditory information through two separate, distinct channels, which have strict, independent capacity limits. Furthermore, this describes how individuals process information through five distinct mental stages. Initially, learners filter specific words and images from the provided material to focus on what is most relevant. These isolated elements are then structured into logical verbal and visual frameworks within the mind. The final stage involves merging these frameworks with an individual's existing knowledge to ensure deep understanding. Furthermore, the theory identifies three types of cognitive demands that impact a person's limited mental capacity during this process. Effective learning depends on managing unnecessary distractions while supporting the essential effort required to organize and interpret new information (see Figure 4).

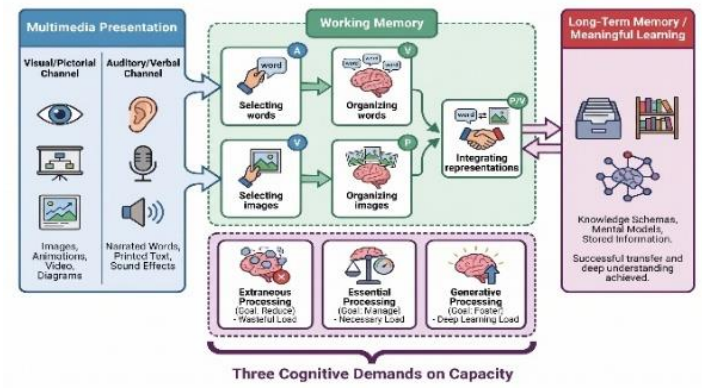


Figure 4. Cognitive Theory of Multimedia Learning (Adapted from Mayer, 2021)

To fulfill the mandates of the National Curriculum Framework of Maldives (National Institute of Education, 2015) and cultivate the 21st century competencies such as critical thinking, collaboration, communication, creativity, culture, and connectivity, students must successfully navigate high intrinsic cognitive load, as scientific inquiry inherently demands abstract conceptualization (Solikah, 2026; Sweller, 2010). While traditional didactic teaching has long been effective, it may encounter limitations when trying to sustain the attention of modern adolescent learners (Kaushik et al., 2024). Given students' increasing interaction with digital devices and the potential cognitive impacts of excessive short-video consumption, educators should consider updating their instructional methodologies to better align with these evolving learning preferences. (Chardonnens, 2025). According to Mayer's (2021) Cognitive Theory of Multimedia Learning, presenting information through both the visual and auditory channels simultaneously creates a highly engaging, multi-sensory learning

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environment. Theoretically, integrating structured, short-duration multimedia into science curricula should provide the necessary stimulus to support the focus of contemporary learners, offering a valuable complement to conventional instructional methods (Slemmons et al., 2018).

When educators attempt to incorporate engaging multimedia elements, a cognitive bottleneck often occurs due to the inclusion of seductive details (Harp & Mayer, 1998; Sundararajan & Adesope, 2020). According to those studies, seductive details are “interesting and irrelevant details”. When instructional materials include seductive details, learners demonstrate a decreased capacity to retain essential structural concepts and exhibit poorer performance when applying those core ideas to problem-solving tasks (Sundararajan & Adesope, 2020). The internal mechanism of the seductive details effect can be understood as a catastrophic cognitive crash. During high-intrinsic science lessons, a student's working memory is operating near full capacity. Introducing non-essential hooks, such as unrelated humour, generates an overwhelming surge of extraneous cognitive load that monopolizes the learner's remaining mental resources. This sensory overload actively starves the brain of the capacity needed for germane processing, resulting that no meaningful schema construction can occur and fundamentally disrupting the transfer of scientific knowledge (Park et al., 2011).

To make the video an efficient educational material, the seductive details should be completely removed and fully aligned with the Signalling and Segmenting principles (Mayer, 2021). Effectiveness of this was empirically shown by the study by Ibrahim et al. (2012). Van Gog (2021), explained about the Taxonomy of Instructional Signaling Cues in detail (see Table 2).

Table 2. Taxonomy of Instructional Signaling Cues (Adapted from van Gog, 2021)

Cue category	Specific signaling technique	Instructional phase
Text - Based Cues	Preview Summaries	Highlights the structural organization of the material before the lesson begins.
	Explicit Verbal Directives	Uses sentences inserted directly into the text to explicitly guide attention to an accompanying picture.
Subtle Text Cues	Font Emphasis	Draw attention to key terms using bolding or specific font colors (e.g., red text for core vocabulary).
	Vocal Intonation	Emphasizes structural spoken text through deliberate changes in the instructor's vocal pitch or volume.
Visual/ Picture Cues	Extrinsic Additions	Directs spatial attention by overlaying new elements, such as graphical arrows, onto a diagram.
	Intrinsic Modifications	Modifies existing visual elements without adding new information (e.g., dynamically changing the color of an anatomical label as it is spoken).
	Shading and zooming	Increases visual saliency by temporarily dimming peripheral elements or zooming in to isolate the specific focal point.
Text-Picture Cues	Color Coding	Facilitates integration by matching the exact color of a specific term in the text to its corresponding structure in the diagram.

According to Mayer and Pilegard (2014), it is easier to learn when multimedia learning material is broken into segments rather than delivering as a continues unit. Furthermore, they emphasise that it contributes to reducing the cognitive load. Especially for students who have lower levels of prior knowledge such as middle school students, these segmented animation videos are proven to be effective (Spanjers et al., 2010). Educators should introduce system-paced interruptions that strictly segment the video at each discrete procedural step (Biard et al., 2018).

The pedagogical necessity for this strict segmentation is driven by a phenomenon defined in cognitive psychology as the transient information effect (Wong et al., 2012). Unlike static physical diagrams or text, digital video presents information that is inherently fleeting. Consequently, learners must hold earlier

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visual and auditory information in their limited working memory while simultaneously attempting to process new, incoming digital stimuli. Wong et al. (2012) demonstrated that when the intrinsic complexity of the academic material is high, this continuous, transient flow of multimedia information theoretically saturates working memory capacity, potentially leading to cognitive overload and a catastrophic loss of comprehension. Therefore, anticipating and mitigating this transient information effect is a critical prerequisite when engineering multimedia for complex middle school science curricula.

For decades, the BSCS 5E Instructional Model has dictated the sequence of science education, shaping how curricula are designed and delivered from individual lessons to entire academic programs. The traditional framework guides students through a constructivist cycle: it begins by capturing interest and accessing prior knowledge (Engagement), allows for hands-on investigation (Exploration), provides direct conceptual instruction (Explanation), extends understanding through application (Elaboration), and concludes by assessing learner progress (Evaluation) (Bybee et al., 2006).

Traditional constructivist teaching procedures often proceed as though working memory possesses no relevant limitations when processing novel information. Consequently, inquiry-based instruction places a substantial burden on cognitive resources, relying on the assumption that a learner has an uncompromised working memory capacity to handle the load (Kirschner et al., 2006). However, in the modern context, students' baseline attention may be challenged by the extensive use of digital media and short-video platforms (Li et al., 2026; Mona et al., 2026). This is where the traditional 5E Instructional Model may encounter a pedagogical bottleneck. While contemporary learners are highly technologically fluent, frequent digital immersion can sometimes compete with the cognitive resources required for sustained critical thinking and deep analytical processing (Shatto & Erwin, 2016). Consequently, for educators striving to maintain meaningful classroom focus, these evolving media habits present both instructional barriers and novel avenues for teaching(Rothman, 2016). Generation Z learners function as "observers" who overwhelmingly prefer acquiring new information through digital video content rather than traditional, text-heavy instruction. Furthermore, they favor intrapersonal, self-paced learning environments that allow them to process concepts independently before engaging in collaborative tasks. Consequently, traditional instructional frameworks must integrate targeted multimedia and self-directed pacing to remain pedagogically viable for this demographic (Seemiller & Grace, 2017).

To address these cognitive barriers and changing digital habits of the students, this study proposes an adaptation of the 5E Instructional Model where the post-lesson multiple-choice quiz serves a dual pedagogical purpose: functioning as the formal "Evaluate" phase while simultaneously providing a quantitative metric for immediate retention. The integration of this quiz leverages the "testing effect" (Roediger & Karpicke, 2006), a cognitive phenomenon where taking a memory test goes beyond merely assessing knowledge to act as a powerful means of improving learning and enhancing later retention. Because the working memory of contemporary adolescents is compromised by rapid decay, this evaluation phase must occur immediately; implementing such retrieval practice has been systematically proven by Agarwal et al. (2021) to yield robust learning benefits across a wide range of real-world classroom settings and educational levels.

2.2. Review of Related Empirical Studies

The theoretical limits of working memory outlined by CTML are practically reflected in students' digital viewing habits. In a landmark empirical analysis of nearly seven million instructional video sessions, Guo, Kim, and Rubin (2014) identified a strict biological boundary for multimedia engagement, establishing what is now commonly referred to as the 'Under-6 Rule.' Their data demonstrated that student engagement remains optimal only for the first six minutes of a video; beyond this threshold, attention drops precipitously, and learners begin to disengage or abandon the material entirely, regardless of the video's total length or production quality. While this metric was originally established through massive open online courses (MOOCs), it provides a crucial cognitive baseline for middle school environments. If adult learners experience catastrophic cognitive fatigue after

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six minutes of continuous digital instruction, the attention-depleted adolescent brain requires even stricter temporal boundaries to prevent extraneous load when integrating multimedia into formal science education.

Recent research underscores the value of concise multimedia in middle school science education. For instance, Slemmons et al. (2018) demonstrated that while shorter instructional videos produced only marginal gains in immediate assessment scores, they significantly enhanced students' self-reported focus and classroom engagement. However, because this study examined video pacing strictly within a flipped classroom setting, it leaves open the question of how targeted, short-form multimedia might perform when actively integrated into the structured phases of the 5E instructional model.

Recent research confirms that pairing structured inquiry frameworks with digital multimedia significantly enhances secondary science education. For instance, Guruloo et al. (2024) demonstrated that delivering a structured inquiry curriculum through smartphone-based virtual laboratories significantly improved students' science process skills compared to conventional teaching. Crucially, the researchers concluded that these academic gains stemmed from the structured pedagogical design rather than the mere presence of technology. However, while this highlights the value of modernizing inquiry-based learning with digital tools, the intervention focused heavily on extended laboratory skill acquisition. Because it did not address cognitive fatigue or utilize short video hooks and immediate retrieval quizzes, it leaves a critical gap regarding how structured inquiry must be adapted for immediate knowledge retention in attention-depleted learners.

To directly combat attention decay during digital instruction, Szpunar et al. (2013) demonstrated that interpolating lectures with frequent memory tests significantly reduces mind-wandering and lowers subjective cognitive demand. Their experiments confirmed that short-burst quizzes successfully sustain task-focused attention and tangibly improve overall retention. However, because this research evaluated standard lecture formats, a critical gap remains regarding how immediate retrieval practice functions when specifically integrated into a constructivist 5E science framework to secure knowledge for attention-depleted middle schoolers.

To synthesize these theoretical perspectives, this study proposes a linear conceptual framework (see Figure 5) that maps the instructional sequence to expected cognitive outcomes. The intervention begins with the Instructional Method, directly comparing a video-integrated 5E model (Bybee et al., 2006) against traditional direct instruction. Within the experimental condition, specific Multimedia Features—such as AI-generated aesthetics, strict temporal segmenting under six minutes (Guo et al., 2014), and targeted visual signaling (van Gog, 2021)—are applied to optimize information delivery. Grounded in the Cognitive Theory of Multimedia Learning (Mayer, 2021), these features are designed to actively Manage Cognitive Load by minimizing extraneous distractions while helping students navigate the intrinsic difficulty of the science syllabus (Sweller et al., 2019). Ultimately, this deliberate load management theoretically mitigates the risk of working memory saturation, which directly impacts Academic Retention, measured quantitatively in this study through immediate conceptual recall on post-lesson multiple-choice quizzes.

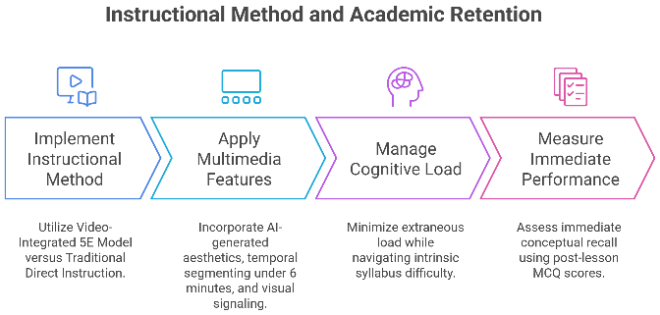


Figure 5. Conceptual framework illustrating the theoretical progression from instructional method to academic retention via multimedia features and cognitive load management.

2.3. Research Gap

While existing literature confirms that short-form multimedia enhances engagement (Slemmons et al., 2018), structured inquiry frameworks boost process skills (Guruloo et al., 2024), and immediate quizzes mitigate cognitive fatigue (Szpunar et al., 2013), these pedagogical mechanisms are largely studied in isolation. A critical gap exists regarding the synthesis of these elements within contemporary secondary science education. Specifically, limited empirical

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research was identified that adapts the traditional 5E Instructional Model by integrating short-video hooks and immediate multiple-choice retrieval practice as a unified mechanism to support the engagement of modern adolescent learners. Therefore, this study addresses this gap by quantitatively evaluating how a multimedia-integrated 5E framework impacts the immediate post-lesson performance of Grade 7 and 8 science students.

3. Methodology

3.1. Research Design

Since this was conducted in a real – world context at Miza Educational Institute, Hulhumalé, the study is done as a quantitative, quasi-experimental non-equivalent groups design, because it utilized pre-existing classes, making true random assignment of students impossible. In this experiment the independent variable was the instructional delivery method where the experimental group received the video-integrated 5E model and the control group received traditional direct teaching. The dependent variable was immediate post-lesson performance, measured using post-lesson quiz scores (see Table 3).

Table 3. Quasi-Experimental Post-Test-Only Crossover Design

Phase	Intact Class A	Intact Class B	Data collection
Trial 01	Experimental treatment (Video-Integrated 5E Model)	Control treatment (Traditional direct teaching)	Immediate MCQ post test
Trial 02	Control treatment (Traditional direct teaching)	Experimental treatment (Video-Integrated 5E Model)	Immediate MCQ post test

3.2. Population and Sample

The research was conducted at the Miza Educational Institute, widely recognized as the largest and most prestigious supplementary educational facility in the Greater Malé region. Known for its rigorous academic framework and high standards, the institute attracts students from various schools across Malé and Hulhumalé islands, an area supporting a broader regional student population of 39,605 including specific local cohorts of 3,009 Grade 7 and 2,912 Grade 8 students across the Greater Malé district, which encompasses 19 government-run national schools alongside private educational facilities (Ministry of Education, 2024).

Because of this regional reach, the purposive sampling of pre-existing, intact classes captured a wide, realistic diversity of baseline knowledge levels and socioeconomic backgrounds. A defining feature of this methodology was the implementation of a crossover design, which was specifically selected to mitigate the constraints of utilizing small intact classes at the participating institute (ranging from 8 to 16 students per subgroup). The intact class that served as the experimental group in the first trial transitioned to act as the control group in the second trial, and vice versa. By counterbalancing the groups, every participating student experienced both instructional methods, allowing them to act as their own controls. Given the high diversity in the students' educational and family backgrounds, this natural rotation effectively leveled the playing field, neutralizing potential differences in baseline aptitude without the need for formal pre-testing.

Furthermore, analyzing this crossover data via a Linear Mixed-Effects Model (LMM) allowed for the mathematical pooling of variance across both trials. After excluding seven incomplete profiles to ensure data integrity, the final analysis utilized a robust total of 115 valid experimental observations derived from 91 unique students. This pooled LMM approach substantially increases statistical power compared to isolated between-subjects analyses, providing sufficient sensitivity to detect the significant developmental interaction effects reported.

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3.3. Instruments for Data Collection

The data collection process for this quasi-experimental study relied on two primary categories of instructional and measurement instruments: the custom-designed multimedia video interventions and the post-lesson multiple-choice quizzes.

3.3.1. Multimedia Instructional Instruments

The experimental intervention utilized custom digital video content designed specifically to align with the Maldives National Syllabus for Grade 7 and 8 Science (National Institute of Education, 2015). To ensure high visual engagement while controlling stylistic consistency, the instructional videos were generated using Google Veo, an advanced artificial intelligence video generation model. The content was purposefully rendered in an anime-style visual aesthetic. This deliberate pedagogical choice is empirically supported by Barak, Ashkar, and Dori (2011), whose research demonstrated that teaching science via animated movies significantly enhances students' thinking skills specifically their science understanding, knowledge implementation, and reasoning ability. Furthermore, their study confirmed that students taught with animated media develop higher motivation to learn science, reporting increased self-efficacy, interest, enjoyment, and a stronger connection between the academic material and their daily lives.

This motivational and cognitive advantage is directly explained through the lens of Mayer's (2021) Cognitive Theory of Multimedia Learning (CTML). Because the anime-style videos leverage simultaneous visual-pictorial and auditory-verbal capabilities, they trigger active, dual-channel cognitive processing without overwhelming the learner. This active engagement successfully bridges the gap between complex thinking skills and sustained student motivation.

3.3.1.1 Generative AI Prompt Engineering and Cognitive Load Calibration

A critical methodological challenge in utilizing generative AI for educational media is the inherent tendency of these models to produce overly complex, visually dense outputs. Unregulated AI generation frequently introduces "seductive details" highly stimulating but academically irrelevant visual elements that monopolize a learner's working memory (Harp & Mayer, 1998). To prevent this catastrophic cognitive crash, the Google Veo prompt architecture was heavily engineered using strict instructional constraints.

The visual generation prompts were explicitly designed to enforce Mayer's (2021) Coherence Principle, which dictates that learning improves when extraneous words, pictures, and sounds are excluded. The prompt architecture utilized a dual-layered command structure:

1. Positive Constraints (What to Include): Prompts mandated a "flat-shaded anime aesthetic," "high-contrast primary colors for scientific elements," and "static, minimalist backgrounds." This ensured that the core scientific phenomena (e.g., an atomic structure or a physics equation) remained the undisputed visual focal point.

2. Negative Prompts (What to Exclude): To systematically weed out seductive details, negative prompts were heavily utilized. The AI was instructed to strictly avoid "dynamic camera movements," "crowded backgrounds," "hyper-realistic lighting," and "superfluous character animations." This rigorous weeding process is empirically validated by Sundararajan and Adesope (2020), whose meta-analysis confirmed that the inclusion of such seductive details severely impairs learners' ability to transfer foundational concepts into long-term memory.

However, a critical balance was required during this curation process. A rigorous distinction was maintained between extraneous 'seductive details' (Harp & Mayer, 1998; Sundararajan & Adesope, 2020) and biologically primary visual cues (Geary, 2008). While transient, highly stimulating background animations and irrelevant narrative elements were systematically eliminated using negative prompts to minimize extraneous cognitive load, essential visual anchors such as distinct biological structures, high-contrast character faces, and specific kinetic pathways were intentionally preserved. Because biologically primary stimuli automatically capture attention by bypassing the effortful executive functions of the prefrontal cortex, this deliberate curation ensured that the sanitization of seductive details did not inadvertently wash away the evolutionary mechanisms required to organically anchor student attention. Building upon

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these primary biological anchors, precise secondary signaling cues were then engineered into the presentations during post-production.

Furthermore, precise signaling cues were engineered into multimedia presentations during post-production. These included on-screen text to anchor key terminology, visual highlighting (such as color-coding specific protons and electrons) to direct spatial attention, and vocal tone emphasis by the instructor to underline critical structural concepts. The pedagogical necessity of these specific cues is supported by Ibrahim et al. (2012), who demonstrated that implementing explicit visual and vocal signaling significantly reduces extraneous load and improves immediate retention, particularly for novice learners attempting to process complex scientific phenomena(see Figure 7).

Finally, to prevent the depletion of students' working memory, all multimedia materials were strictly bound by the "Under-6 Rule." This parameter is grounded in the landmark empirical research by Guo, Kim, and Rubin (2014), who analyzed nearly seven million instructional video sessions and determined that student engagement drops precipitously after the six-minute mark, regardless of the total video length. By restricting any continuous video segment to a maximum duration of six minutes, the intervention ensured the content remained within the optimal attention span of the target demographic while effectively mitigating cognitive fatigue. To demonstrate the specific visual aesthetic, pacing, and signaling cues utilized in this study, a sample of the experimental multimedia intervention has been recorded.

3.3.1.2. Development of the Multimedia Intervention

To ensure replicability and maintain pedagogical rigor, the multimedia intervention was developed through a structured, researcher-mediated pipeline:

Scientific Content and Scripting: Core scientific concepts were drawn directly from the Maldives National Syllabus. Acting as both researcher and classroom instructor, the author drafted the foundational instructional scripts. A large language model (Gemini) was then used iteratively to refine the pacing and ensure the vocabulary remained developmentally appropriate for early adolescents.

Visual Generation and Animation Pipeline: Foundational static images were generated using Nano Banana Pro. To prevent visual clutter, the prompts were specifically engineered to yield a flat-shaded anime aesthetic, embedding structural signaling cues directly into the initial text. These static frames were then processed through Google Veo, which animated them into discrete 8-second video segments while preserving the established pedagogical constraints(see Figure 6).

Post-Production, Stitching, and Narration: The 8-second animated segments were imported into CapCut for final compositing. Here, the distinct clips were stitched into a cohesive sequence and synchronized with AI-generated voice narration. Additional explicit signaling cues, such as color-coded text overlays and directional arrows, were overlaid during this phase. Final video lengths were strictly capped at 90 seconds for engagement hooks and 4.5 minutes for instructional summaries.

Pedagogical Validation: Because generative AI remains susceptible to hallucinatory outputs, the tools were never allowed to operate autonomously. Prior to classroom deployment, the researcher conducted a rigorous, frame-by-frame audit of every video. This manual review ensured absolute scientific accuracy, verifying that all visual phenomena, voiceovers, and on-screen text aligned perfectly with national syllabus indicators and remained free of seductive details

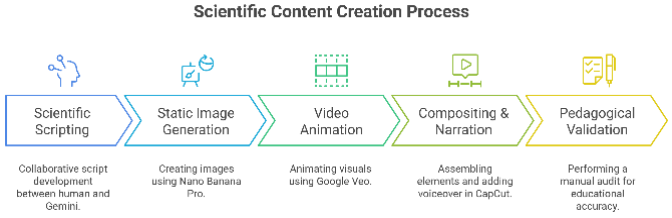


Figure 6. Linear progression of the AI-integrated multimedia production pipeline. The flowchart illustrates the sequential integration of human-mediated scripting, *generative AI tools, and final pedagogical validation to ensure replicability and adherence to cognitive load constraints.*

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(a) (b) (c)

Figure 7. Implementation of Multimedia Signaling Cues and Anime-Style Aesthetic in Experimental Video Interventions. **(a)** Atomic Definition (Protium): On-screen text anchoring provides a direct, low-load definition, while distinct red and blue color-coding reduces extraneous search. **(b)** Formula Structuring: A semi-transparent text box groups related formulas with high-contrast typography, and character interaction directs focus to the general area of content. **(c)** Embedded Attention: The formula (W = m x g) is embedded creatively on the lens to link seeing with understanding, utilizing a high-focus composition to draw immediate visual attention. (Sci-Sensei, n.d.)



Figure 8. The images demonstrate the practical application of the AI-generated experimental intervention at Miza Educational Institute. Photographs were deliberately framed from the rear of the classroom to maintain strict ethical compliance and ensure the anonymity of the minor participants.

3.3.2. Measurement Instruments (Retrieval Quizzes)

To measure immediate post-lesson performance and fulfill the "Evaluate" phase of the adapted 5E model, post-lesson quizzes were administered instantly following the instructional phase for both the experimental and control groups. The quizzes consisted entirely of comprehensive Multiple-Choice Questions (MCQs) designed to cover the exact topics taught during the session. To ensure absolute measurement equivalence, the exact same multiple-choice quiz was administered to both the experimental and control cohorts for each respective science topic.

The total number of questions on each quiz was not fixed; rather, it was dynamically adjusted to ensure comprehensive assessment of the specific lesson content. Each item was scored objectively (1 point for a correct answer, 0 points for an incorrect answer). Because the total number of items varied depending on the conceptual density of the topic, all raw scores were systematically converted into percentages. This conversion ensured a standardized, reliable quantitative comparison across all experimental and control crossover trials.

3.3.3. Validity and Reliability of Instruments

Content validity for all measurement instruments was established through strict, direct alignment with the official Maldives National Curriculum Framework (National Institute of Education, 2015). Every MCQ was explicitly mapped to specific curricular indicators, ensuring the questions directly measured the scientific content delivered via both the multimedia interventions and the direct teacher instruction. To regulate assessment difficulty and ensure a comprehensive evaluation of student understanding, the items were systematically constructed utilizing the revised Bloom's Taxonomy (Anderson & Krathwohl, 2001), balancing foundational recall with higher-order conceptual application.

Reliability was secured through the standardized design and objective dichotomous scoring of the multiple-choice format. Furthermore, because the identical, syllabus-aligned quiz instrument was administered to both the experimental group and the control group under identical temporal conditions (immediately post-instruction), environmental testing inconsistencies were neutralized. This robust crossover implementation allowed the variations in the final percentage scores to be confidently attributed to the instructional delivery method rather than inconsistencies in the measurement tool itself.

3.4. Procedure / Data Analysis Plan

3.4.1. Experimental Procedure

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The pedagogical intervention was administered during standard, scheduled science periods at the Miza Educational Institute. To replicate realistic school conditions and ensure the study's ecological validity, each instructional session was strictly time-bound to 45 minutes, directly aligning with the standard timetabled class duration for these grades at the Miza Educational Institute. The execution of the video-integrated 5E instructional model (Bybee et al., 2006) required rigorous temporal management to ensure cognitive resources were optimally utilized rather than exhausted.

For the experimental group, the 45-minute lesson was systematically divided into four distinct phases, strategically mapped to the cognitive fluctuations of the modern adolescent learner (see Figure 9).

Phase 1: The Engagement Hook (Minutes 0:00 – 1:30) The lesson commenced immediately with a short, AI-generated anime-style video hook. During the first ninety seconds of a class, students transitioning from other environments frequently experience high levels of extraneous cognitive load and distracted thinking. This rapid visual stimulus was designed to actively disrupt that cognitive fatigue. By leveraging the visually stimulating anime aesthetic without introducing heavy academic content, the hook instantly oriented the students toward the core scientific phenomena of the day, successfully fulfilling the "Engage" phase of the 5E model (Bybee et al., 2006).

Phase 2: Direct Teacher Instruction (Minutes 1:30 – 16:30) Immediately following the hook, the researcher transitioned into the "Explain" phase using streamlined, traditional direct instruction. Because the students' attention had been successfully captured by the video, their working memory was primed for dual-channel processing. (Mayer, 2021) This 15-minute window allowed for the verbal delivery of complex abstract concepts, detailed formula breakdowns, and live student-teacher interaction. During this phase, all extraneous multimedia was turned off to eliminate split-attention effects (Sweller et al., 2019). The instructor relied on localized whiteboard signaling and direct questioning to guide schema construction, ensuring the intrinsic load of the scientific material was managed efficiently.

Phase 3: Multimedia Summary (Minutes 16:30 – 21:00) Before moving to the assessment, a final animated summary video was displayed. Remaining well under the six-minute cognitive threshold established by Guo et al. (2014), this 4.5-minute phase served to solidify the newly constructed schemas. The summary video utilized the same anime characters introduced in the hook, creating a cohesive narrative structure. This phase visually mapped the abstract concepts discussed during direct instruction, allowing students to integrate the auditory-verbal lessons with visual-pictorial representations (Mayer, 2021) before their cognitive endurance began to wane.

Phase 4: Immediate Retrieval Practice (Minutes 21:00 – 45:00) The remaining 24 minutes of the class were dedicated exclusively to the "Evaluate" phase. Students were administered the multiple-choice quiz and required to complete it under standard, silent examination conditions. This extended period served a dual pedagogical purpose. First, it provided the quantitative data necessary for this study's immediate retrieval metrics. Second, it leveraged the "testing effect" (Roediger & Karpicke, 2006). By forcing students to actively retrieve the newly acquired schemas immediately after the instructional phases, this practice naturally reduced mind-wandering and tangibly solidified the neural pathways required for long-term memory consolidation (Agarwal et al., 2021; Szpunar et al., 2013).

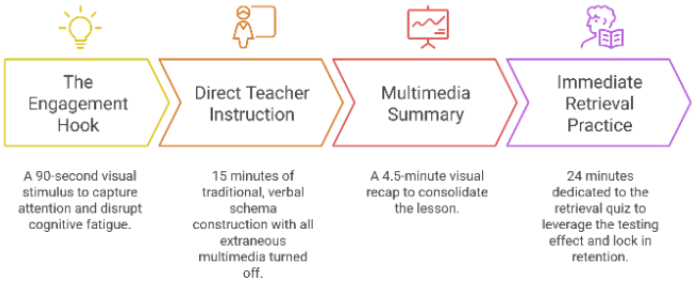


Figure 9. Pedagogical timeline and structural breakdown of the 45-minute video-integrated experimental lesson.

For the control group, the 45-minute lesson was structurally engineered to isolate the timing of the multimedia integration while maintaining absolute parity in overall content exposure and instructional time. These students received the exact same 15 minutes of direct teacher instruction, utilizing identical scripts and whiteboard signaling to prevent any bias in teacher attention or pacing. However, rather than

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viewing the AI multimedia before the assessment, the control group transitioned immediately into the retrieval practice phase. To perfectly balance the 45-minute period and ensure educational equity, the control group was shown the engagement hook and the multimedia summary after all quizzes had been collected. This critical methodological design ensured that both cohorts experienced identical teacher pacing and equal exposure to the novelty of the digital medium within the same class period. Consequently, the sequencing of the multimedia prior to the assessment was successfully isolated as the sole independent variable impacting the immediate retrieval scores.

3.4.2. Cross-over implementation

To neutralize the inherent limitations of using non-equivalent, intact classes (such as varying baseline intelligence or socioeconomic factors), a crossover design was employed. Trial 1 was conducted during the first week of the study. A one-week (7-day) interval was implemented before conducting Trial 2. This natural gap was not an arbitrary design choice, but rather a strict structural requirement of the institute's academic timetable, as the participating classes are allocated a single science period per week.

To prevent content carryover effects between the two phases, Trial 1 and Trial 2 focused on completely independent, non-sequential science topics drawn from the Maldives National Syllabus. This timetable-driven interval provided a significant methodological advantage by naturally mitigating immediate testing fatigue and resetting instructional novelty. During the second week, the intact class that served as the experimental group in Trial 1 crossed over to act as the control group, while the former control group received the experimental multimedia intervention. This ensured all participating students eventually benefited from the multimedia-integrated method while allowing the subsequent Linear Mixed-Effects Model (LMM) to cleanly isolate period and topic effects.

3.4.3. Data Analysis Plan

Upon the completion of both trials, the quantitative data derived from the immediate post-lesson MCQ quizzes were tabulated and cleaned. The analytical procedure involved two distinct stages:

1. Descriptive Statistics: Initial analyses calculated the mean scores, standard deviations, and standard errors for both the experimental and control groups across the Grade 7 and Grade 8 cohorts to provide a macro-level overview of immediate post-lesson performance.

2. Inferential Statistics: To rigorously evaluate the crossover structure and isolate period effects, the data were analyzed using Linear Mixed-Effects Models (LMM) in R (utilizing the lme4 and lmerTest packages). Within the model, "Instructional Method" and "Trial" were designated as fixed effects. To account for baseline ability variations and track repeated measures, “Student_ID” a unique numerical identifier assigned to each participant to strictly preserve the anonymity of the students—was utilized as a random intercept. A significance level of $\alpha=0.05$ was established to determine the statistical significance of the instructional method's impact on student performance.

4. Results and Discussion

4.1. Grade 7 Cohort Analysis

To evaluate the immediate academic retention of Grade 7 students, test scores were analyzed collectively across both crossover trials. The descriptive statistics comparing the AI-generated multimedia intervention to traditional instruction are presented below (see Table 4).

Table 4. Grade 7 Descriptive Statistics by Trial

Method	Trial	N	Mean	SD	SE
AI Video - integrated instructions	1	12	56.25	15.24	4.40
Traditional instructions	1	8	45.62	20.08	7.10
AI Video - integrated instructions	2	12	70.83	14.12	4.07
Traditional instructions	2	10	50.00	21.86	6.91

A linear mixed-effects model (LMM) was utilized to assess these differences while controlling for repeated measures and period effects. The model revealed a

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significant main effect of the instructional method (see Table 5).

Table 5. Linear Mixed-Effects Model Predicting Grade 7 Test Scores

Predictors	Estimates	Std. Error	CI	t	p	df
(Intercept)	59.41	4.40	50.49 – 68.33	13.50	**<0.001**	37.00
Method [Traditional]	-17.06	5.13	-27.45 – -6.67	-3.33	**0.002**	37.00
Trial [2]	9.79	4.88	-0.09 – 19.67	2.01	0.052	37.00
Random Effects						
σ^2	206.42					
$\tau_{00\ Student_ID}$	109.47					
ICC	0.35					
$N_{Student_ID}$	31					
Observations	42					
Marginal R^2 / Conditional R^2	0.227 / 0.495					

Students scored significantly lower under traditional instruction (Estimate = -17.06, 95% CI [-27.45, -6.67], p = 0.002) when compared to the AI Video baseline. The accompanying boxplot visually reinforces this dynamic, highlighting a clear performance advantage for the multimedia intervention within the younger cohort.

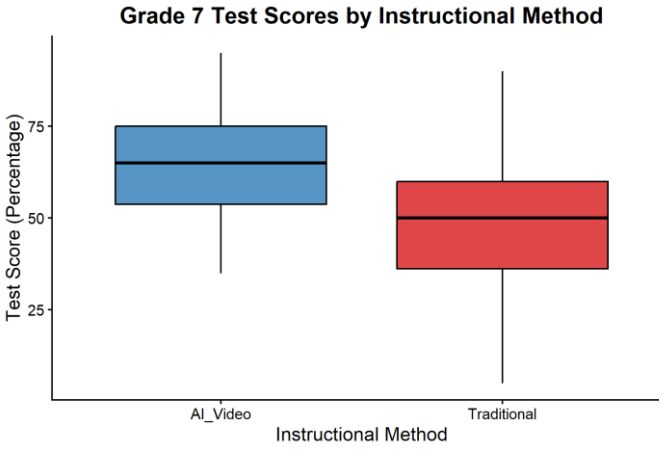


Figure 10. Boxplot illustrating the distribution of Grade 7 test scores by instructional method. The visualization compares the median performance, interquartile range, and score variance between students who received the AI-generated multimedia intervention (blue) and those taught via traditional direct instruction (red). Data-Based Finding: This figure strictly presents empirical data derived directly from the measured post-lesson retrieval quiz scores.

4.2. Grade 8 Cohort Analysis

An identical analytical framework was applied to the Grade 8 cohort. The mean scores and standard errors across both instructional methods and trials are detailed in Table 6.

The LMM analysis for Grade 8 demonstrated a stark reversal in student performance (see Table 7). The model confirmed that students achieved significantly higher scores when taught using traditional direct instruction (Estimate = 17.01, 95% CI [8.67, 25.34], p < 0.001) rather than the multimedia baseline. This upward shift is captured in the boxplot below (Figure. 11), confirming that the older students benefited substantially from a traditional pedagogical approach.

Table 6. Grade 8 Descriptive Statistics by Trial

Method	Trial	N	Mean	SD	SE
AI Video - integrated instructions	1	27	41.48	15.62	3.01
Traditional instructions	1	15	55.33	17.27	4.46
AI Video - integrated instructions	2	17	51.18	19.33	4.69
Traditional instructions	2	14	72.14	18.47	4.94

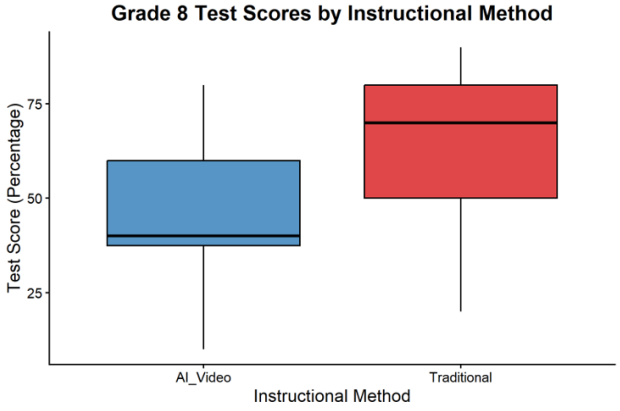


Figure 11. Boxplot illustrating the distribution of Grade 8 test scores by instructional method. The visualization compares the median performance, interquartile range, and score variance between students who received the AI-generated multimedia intervention (blue) and those taught

via traditional direct instruction (red). Data-Based Finding: This figure strictly presents empirical data derived directly from the measured post-lesson retrieval quiz scores.

To synthesize these contrasting findings, the following bar chart (Figure.12) provides a comprehensive visualization of both cohorts across all trials. This side-by-side comparison clearly illustrates the developmental divergence: AI multimedia scaffolding elevated Grade 7 outcomes, while traditional direct instruction proved superior for Grade 8.

Table 7. Linear Mixed-Effects Model Predicting Grade 8 Test Scores

Predictors	Estimates	Std. Error	CI	t	p	df
(Intercept)	40.36	3.07	34.23 – 46.48	13.15	**<0.001**	68.00
Method [Traditional]	17.01	4.18	8.67 – 25.34	4.07	**<0.001**	68.00
Trial [2]	12.61	4.13	4.36 – 20.86	3.05	**0.003**	68.00
Random Effects						
σ^2	302.04					
$\tau_{00\ Student_ID}$	0.00					
$N_{Student_ID}$	60					
Observations	73					
Marginal R^2 / Conditional R^2	0.284 / NA					



Figure 12. Comparison of mean test scores by instructional method and trial across Grade 7 and Grade 8 cohorts. The grouped bar chart visualizes the mean immediate retrieval quiz scores for the AI-generated multimedia intervention (blue) and traditional direct instruction (red) across the two-week crossover design. Error bars denote the standard error of the mean. The side-by-side panels synthesize the developmental interaction effect, illustrating the multimedia advantage for Grade 7 versus the traditional instruction advantage for Grade 8 across both trials. Data-Based Finding: This visualization represents strictly empirical findings derived from quantitative quiz results.

4.3. General Discussion and Findings

The empirical findings of this study reveal a complex, load-dependent dynamic regarding the integration of AI-generated, anime-style multimedia instruction in secondary science classrooms. Across the four experimental and crossover trials, the data rejected a uniform response to video-integrated instruction. Instead, it demonstrated a sharp developmental divergence between the Grade 7 and Grade 8 cohorts.

For the Grade 7 cohort, the linear mixed-effects model (LMM) confirmed that the multimedia intervention provided a significant educational advantage. Students scored significantly lower under traditional instruction ($p = 0.002$) compared to the AI Video baseline. This indicates that younger adolescent learners benefit directly from the visual-pictorial and auditory-verbal channels working in tandem. By utilizing the character-driven narrative and anime aesthetic, the multimedia served as an effective cognitive anchor for foundational science schemas.

Conversely, the LMM analysis for the Grade 8 cohort yielded highly significant results ($p < 0.001$) in the opposite direction. Traditional direct instruction vastly outperformed the multimedia baseline. This unexpected outcome challenges the generalized assumption that modern digital natives universally thrive under high-stimulus multimedia conditions. For older Grade 8 students tackling structurally dense curriculum requirements, we theorize that the anime-style visual presentation introduced an unintended cognitive tax despite the rigorous adherence to the "Under-6 Rule" and the systematic elimination of what were originally perceived to be seductive details. Rather than acting as a cognitive bridge, the visually dense media likely competed with the core instructional content for limited working memory resources. As a result, traditional direct instruction proved to be a much more efficient delivery mechanism for immediate retrieval in high-complexity environments.

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While mean scores indicate overall instructional efficacy, the standard deviation (SD) reveals important dynamics regarding classroom equity. For the Grade 7 cohort, the AI multimedia intervention consistently compressed the variance in student scores. The AI Video group maintained a tighter SD of 15.24 in Trial 1, which narrowed further to 14.12 in Trial 2. In contrast, the traditional instruction groups exhibited much wider score spreads, recording SDs of 20.08 and 21.86. This confirms that AI-generated media actively compresses variance for younger students, functioning as an effective pedagogical equalizer when the intrinsic cognitive load is manageable.

Conversely, for the Grade 8 cohort, the fragmentation of test scores remained relatively consistent across all treatments. The standard deviations for the AI multimedia groups (15.62 and 19.33) closely mirrored those of the traditional instruction groups (17.27 and 18.47). This indicates that under the high intrinsic load of the Grade 8 curriculum, the variance in student performance is driven primarily by the inherent difficulty of the science topics rather than the instructional method itself. Because individual working memory capacity naturally varies among adolescents, highly complex subjects inevitably produce a wider spread of scores.

However, while the fragmentation remained consistent across both treatments, the traditional direct instruction successfully shifted the entire Grade 8 cohort's performance upward. This suggests that while traditional teaching cannot entirely eliminate the natural achievement gap associated with high cognitive load, it serves as a highly reliable delivery mechanism that maximizes overall schema acquisition without exacerbating classroom variance.

4.4. Theoretical and Pedagogical Implications

These contrasting outcomes offer a valuable contribution to the ongoing discourse surrounding Mayer's (2021) Cognitive Theory of Multimedia Learning (CTML). While CTML generally warns against extraneous visual elements, the present findings highlight a critical boundary condition: the learner's baseline academic load.

The divergent results between the cohorts can be explained through the interaction between the seductive detail effect and intrinsic cognitive load. Research indicates that the detrimental impact of seductive details is heavily dependent on the baseline difficulty of the instructional task; while seductive details impair learning in high cognitive load conditions, they can actually improve motivation and performance when the intrinsic cognitive load is low (Park et al., 2011; Park et al., 2015). Under a low cognitive load condition, such as listening to narration, seductive details do not interfere with learning and can lead to a compensatory, motivating effect mediated by situational interest.

For the Grade 7 cohort, the inherent complexity of the early secondary science curriculum (National Institute of Education, 2015) generated a manageable intrinsic cognitive load. Consequently, students possessed sufficient working memory capacity to process the anime-style visuals. In this low-load environment, the dynamic media operated not as a seductive distractor, but as an effective motivational anchor that enhanced immediate schema acquisition.

However, as academic rigor escalated in the Grade 8 syllabus (National Institute of Education, 2015) introducing abstract scientific knowledge the intrinsic cognitive load naturally spiked. In this high-load condition, the students' working memory was already operating near maximum capacity. The data strongly suggests that the visually rich, anime-style multimedia pushed the learners toward cognitive overload. While cognitive load was not directly measured physiologically, we hypothesize that this induced a phenomenon similar to the seductive detail effect, actively disrupting the formation of coherent mental models. For these older cohorts, the cognitive architecture was better optimized for streamlined, text-and-speech-dominant direct instruction where extraneous visual elements were minimized to preserve essential processing capacity.

However, this necessary minimization introduces a critical boundary condition for instructional designers: navigating the pedagogical tension between eliminating seductive details and preserving primary biological cues. Stripping a multimedia presentation of all dynamic visual elements risks neutralizing the Signaling Principle, leaving learners without the necessary visual anchors to process complex scientific phenomena. The efficacy of AI-integrated media relies on a precise calibration filtering out decorative visual noise while meticulously retaining the evolutionary

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and structural cues that naturally tether the learner's working memory to the core learning objective.

4.4.1. The Element Interactivity Threshold

To fully understand the divergent results between the two cohorts, the intrinsic difficulty of the respective syllabi must be analyzed through the lens of Element Interactivity (Sweller, 2010). Element interactivity refers to the extent to which the components of a learning task interact with one another. When elements do not interact, they can be learned sequentially without heavily burdening working memory. For the Grade 7 cohort, foundational science topics often present low element interactivity. Concepts such as basic biological definitions or individual atomic components can be processed in isolation. Consequently, the students' working memory capacity did not appear to be overwhelmed, allowing the anime-style multimedia to function as an effective, engaging schema-builder.

Conversely, the Grade 8 curriculum introduces highly interactive elements. In these high-element interactivity tasks, students must simultaneously hold multiple, interacting variables in their working memory to understand the underlying phenomenon. Because the intrinsic cognitive load was already operating at maximum capacity, it is highly probable that the introduction of visually rich multimedia pushed the total cognitive demand beyond the biological limits of the students' developing executive functions.

4.4.2. The Transient Information Effect

This cognitive overload in the older cohort was further exacerbated by the inherent nature of digital video, a phenomenon defined in educational psychology as the Transient Information Effect (Wong et al., 2012). Unlike static text or physical whiteboard diagrams, video presentations provide information that is fleeting. As the anime-style hook and summary videos played, Grade 8 students were forced to maintain the visual and auditory information from previous seconds in their working memory while actively attempting to process the new, incoming information appearing on the screen. While transient information is manageable during low-complexity tasks as evidenced by the Grade 7 results it becomes severely detrimental when combined with the high element interactivity of advanced middle school science concepts.

4.4.3. Working Memory Saturation

The intersection of high element interactivity, transient multimedia information, and the already fragmented attention spans of modern adolescents creates a catastrophic cognitive collision. For the older cohort, the AI-generated visual aesthetics ceased to be a pedagogical scaffold and instead mutated into seductive details. We hypothesize that the adolescent brain, struggling to process interacting science facts while simultaneously attempting to retain the transient flow of the video narrative, simply ran out of processing capacity. As a result, the students in the experimental group failed to construct coherent mental schemas, leading to significantly lower immediate retrieval scores compared to their peers who received streamlined, static direct instruction. This load-dependent pedagogical divergence where multimedia shifts from a motivational anchor in low-complexity environments to an obstructive cognitive barrier in high-complexity environments is visually synthesized in the conceptual matrix below (see Figure 13).

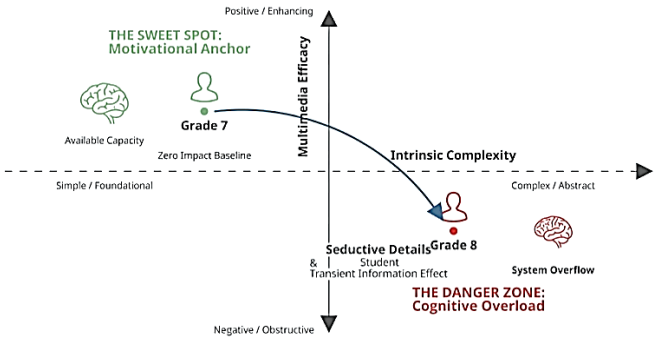


Figure 13. Theoretical model of load-dependent multimedia efficacy. This conceptual diagram synthesizes the study's LMM findings within the framework of Cognitive Load Theory. For Grade 7 learners, where intrinsic complexity is foundational, AI-generated multimedia appears to act as an effective motivational anchor that enhances overall performance. Conversely, as intrinsic complexity scales upward for the Grade 8 curriculum, the empirical score drop suggests that working memory is hypothesized to reach system overflow. In this high-load environment, the transient information effect and visually seductive details likely introduce an unintended cognitive tax, pushing the multimedia intervention into the negative efficacy danger zone. Theoretical Interpretation: Unlike the empirical charts above, this matrix does not plot raw data points. It is a

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conceptual interpretation that synthesizes the study's empirical findings into a broader theoretical model of cognitive load.

4.5. Limitations and Future Research Directions

Several methodological limitations must be acknowledged when interpreting these findings. First, the study utilized a quasi-experimental design with non-randomized, intact classes, meaning true random assignment of individual students to treatment conditions was not possible. Second, the reliance on single-site sampling restricted to the practical classroom parameters at the Miza Educational Institute resulted in relatively small sample sizes within individual grade cohorts. While the crossover design successfully controlled for baseline class ability, these factors may limit the broader generalizability of the findings, and larger, multi-site randomized controlled trials are required in future research. Third, the study evaluated immediate academic retention via post-lesson multiple-choice quizzes. This design measures short-term schema acquisition but does not assess long-term memory consolidation. Future inquiries should incorporate delayed post-tests to determine whether anime-style multimedia creates enduring longitudinal recall advantages despite initial retrieval friction.

Furthermore, while the study rigorously controlled overall instructional time and instructional novelty by exposing the control group to the multimedia intervention after the assessment, minor confounding variables in the immediate pre-test cognitive state must be acknowledged. Transitioning students into a quiz immediately following traditional direct instruction, versus transitioning them after a highly stimulating AI video summary, inherently alters their immediate sensory arousal levels. While this difference in presentation mode is the core focus of the study, future physiological research (such as measuring heart rate or pupillometry) could help determine exactly how much of the score variance is driven by cognitive schema acquisition versus mere sensory stimulation prior to testing.

Additionally, the study's design introduces inherent repeated-measures statistical concerns and possible period and topic effects. An observable macro-trend across the dataset is the universal increase in mean scores during the crossover phase (Trial 2). Initially, this global improvement suggested a powerful instructional acclimation effect (Miguel-Alonso et al., 2023). According to Cognitive Load Theory, students' working memory capacity is inherently restricted when processing "novel information" which includes adapting to a new pedagogical routine and strict quiz pacing. In theory, by the second trial, the instructional procedure itself became familiar, naturally reducing extraneous load and freeing cognitive capacity for deeper schema consolidation. However, our linear mixed-effects model (LMM) analysis indicates that this variance was heavily influenced by fluctuations in the intrinsic difficulty of the specific weekly science topics (Sweller, 2010), rather than pure acclimation. By isolating the 'Trial' effect, the model confirmed that the Week 2 topic provided a statistically significant 12.61-point artificial boost for the Grade 8 cohort ($p = 0.003$). A similar trend appeared in the Grade 7 cohort, which experienced a 9.79-point boost during Week 2, though this effect was only marginally significant ($p = 0.052$).

While the LMM successfully neutralized these period effects to accurately evaluate the two teaching methods, definitively disentangling topic bias from true cognitive acclimation is difficult given that the current study was limited to only two trials. This presents a strong opportunity for future research. By conducting extended longitudinal studies utilizing more trials across a wider developmental gradient, researchers could accurately isolate and measure the correlation between method familiarity and academic performance. Crucially, mapping these varied age groups against the escalating intrinsic cognitive load of the science syllabus would allow educators to pinpoint the exact biological threshold where multimedia transitions from an effective scaffold to an extraneous burden.

Furthermore, the detrimental impact of the transient information effect observed within the Grade 8 cohort necessitates targeted future research into structural multimedia solutions. While this study utilized strict system-paced video segments to maintain temporal consistency across the experimental trials, future investigations should evaluate the efficacy of learner-paced digital environments. Research must explore whether providing students with interactive cognitive scaffolding such as the ability to pause, rewind, or manually dictate the pacing of AI-generated animations can effectively neutralize the transient information

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effect. Determining whether self-paced controls can prevent working memory saturation during high-element interactivity lessons will provide critical pedagogical guidance for integrating generative AI into advanced secondary science curricula.

Finally, while this study utilized immediate retrieval scores as a quantitative proxy for cognitive overload, the internal cognitive mechanism - specifically the exact moment working memory becomes saturated-remains invisible. Future research should integrate continuous physiological measurements, such as eye-tracking technology and pupillometry, during the multimedia instructional phases. Eye-tracking would allow researchers to empirically validate the seductive detail effect in real-time by mapping students' gaze fixations and heat maps. For instance, measuring whether Grade 8 students are disproportionately fixating on the anime characters' aesthetic features rather than the embedded physics formulas would provide concrete biomechanical evidence of split-attention and extraneous cognitive load. Furthermore, analyzing pupil dilation variations between the low-interactivity (Grade 7) and high-interactivity (Grade 8) cohorts would offer a direct, objective measurement of intrinsic cognitive strain. Implementing these neuro-pedagogical tools would elevate the evaluation of the video-integrated 5E model from behavioral inference to precise, real-time neurological observation.

Ultimately, while investigations into learner-paced media controls and delayed post-tests remain valuable, the immediate priority for advancing this research must be twofold. First, implementing larger, multi-school randomized trials is essential to definitively establish the generalizability of these load-dependent findings across broader educational demographics. Second, future experimental designs must prioritize the integration of validated cognitive-load measures pairing established subjective psychometric instruments (such as the Paas Cognitive Load Scale) with objective physiological metrics to directly quantify the exact threshold where digital scaffolding mutates into cognitive overload.

4.6. Threats to Internal Validity and Alternative Explanations

While the LMM analysis indicates a load-dependent developmental divergence, several alternative explanations and threats to internal validity must be addressed. First, to mitigate teacher effects and instructor bias, the exact same researcher delivered the 15-minute direct instruction to both the experimental and control groups using identical, standardized scripts and whiteboard signaling. Second, concerns regarding class composition and prior achievement were neutralized by the crossover design; rather than relying on assumed equivalence between intact classes, students acted as their own controls, and baseline ability was mathematically controlled in the LMM by designating Student_ID as a random intercept. Third, to account for topic and test difficulty, both cohorts were administered the exact same syllabus-aligned quiz immediately post-instruction. While the Week 2 topic proved inherently easier creating a universal score increase the LMM successfully isolated this period effect, ensuring the comparison between teaching methods remained valid. Fourth, to prevent order effects and carryover, a strict 7-day washout period was enforced, and the trials focused on completely non-sequential syllabus topics. Finally, to control for the novelty effect where students might perform better simply due to the excitement of a new digital medium the control group was intentionally shown the AI-generated multimedia immediately after completing their quizzes. This ensured both groups experienced identical sensory stimulation and digital novelty within the 45-minute period, isolating the timing of the multimedia as the sole variable impacting retrieval scores.

5. Conclusion

5.1. Synthesis of Empirical Findings

The contemporary science classroom is increasingly shaped by the shifting cognitive habits of Generation Z and Alpha learners. Ubiquitous smartphone use and the normalization of short-form video consumption have fundamentally altered baseline attention spans, often leaving students with a compromised working memory capacity before a lesson even begins (Firth et al., 2019; Mona et al., 2026). This study aimed to confront this reality directly by adapting the traditional 5E Instructional Model (Bybee et al., 2006), testing whether highly structured, AI-generated anime-style multimedia could capture fractured attention without inducing cognitive overload.

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The data gathered from the crossover trials at the Miza Educational Institute present a nuanced picture that challenges the blanket assumption that "digital natives" inherently learn better through screens. Instead of a universal benefit, we observed a profound divergence in efficacy. Rather than a purely developmental interaction, this divergence appears to be heavily confounded and tied directly to the escalating intrinsic cognitive load of the subject matter between the grades(Sweller, 2010). For the Grade 7 cohort, where foundational science concepts demand a relatively manageable cognitive load, the multimedia integration worked exactly as intended by Mayer's (2021) Cognitive Theory of Multimedia Learning. The dual-channel processing of the anime-style visuals and auditory narrative acted as a highly effective motivational anchor. It provided just enough stimulation to sustain engagement, yielding moderate-to-large practical gains in immediate knowledge retrieval when compared to traditional chalk-and-talk teaching. In an applied educational context, the estimated 17.06-point performance shift observed in the LMM translates to nearly a full letter-grade improvement on a standard academic assessment. This demonstrates that for low-interactivity subjects, brief digital scaffolding provides a highly meaningful boost to baseline schema acquisition within a standard 45-minute class period.

However, the Grade 8 results serve as a critical boundary condition for multimedia integration. Because their curriculum introduces many abstract concepts which demand higher cognitive load, the intrinsic difficulty of the material was already pushing the limits of the students' working memory. In this high-load environment, the visually rich anime media ceased to be a helpful instructional scaffold. Instead, the observed performance drop may be explained by the seductive detail effect (Park et al., 2015; Sundararajan & Adesope, 2020).The aesthetic elements of the AI-generated video aggressively competed for scarce cognitive resources, overwhelming the learners and disrupting their ability to form accurate scientific schemas. For these older students, stripped-back traditional direct instruction which focuses cognitive energy entirely on the core concepts proved significantly more effective, preventing a severe 17.01-point academic penalty that could mean the difference between passing and failing a conceptually dense syllabus topic.

5.2. Pedagogical and Managerial Implications for Instructional Design

For classroom educators, instructional designers, and school administrators, these findings highlight a pressing need for pedagogical calibration. The decision to deploy generative AI tools or video media in the classroom should never be based simply on a desire to modernize a lesson or entertain students; it must be dictated by a careful analysis of the intrinsic difficulty of the material being taught.

When designing lessons around conceptually accessible topics, educators can confidently deploy stimulating, character-driven video hooks to break through cognitive resistance and set a positive tone for the lesson. But when approaching high-stakes, structurally complex scientific phenomena, the managerial imperative flips: educators must ruthlessly eliminate extraneous visual stimuli. In these high-load scenarios, traditional text-and-speech instruction, supported by clear, static signaling cues like vocal intonation or color-coded whiteboards (van Gog, 2021), is the most responsible way to protect a learner's fragile working memory.

This study also reinforces the practical necessity of strict temporal boundaries, specifically the "Under-6 Rule" (Guo et al., 2014). No matter how visually impressive an AI-generated video might be, sustained digital exposure rapidly yields diminishing returns in student focus. By restricting video hooks to a single minute and capping summary videos at three to five minutes and intentionally placing them strictly at the margins of a 45-minute lesson, teachers can harness the motivational pull of digital media without exhausting their students. Pairing this sequence with immediate multiple-choice retrieval practice (Agarwal et al., 2021) ensures that the "Evaluate" phase does more than just measure learning; it actively forces schema consolidation before the students leave the room.

Furthermore, while our LMM analysis indicated that the universal score improvements observed during Trial 2 were heavily influenced by topic difficulty, the crossover structure of this study underscores a critical,

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yet often overlooked, pedagogical principle: the cognitive cost of instructional instability. Modern educators are frequently encouraged to constantly vary their teaching methods and introduce new digital platforms to maintain student interest. However, doing so perpetually triggers the novelty effect, acting as a continuous source of extraneous cognitive load (Miguel-Alonso et al., 2023). Every time a teacher introduces a radically new pedagogical routine, students must expend vital working memory simply figuring out the mechanics of the lesson and processing the routine as "novel information" rather than focusing on the intrinsic science content (Sweller et al., 2011). Therefore, educators should strive for structural predictability. By maintaining a highly consistent pedagogical framework such as a standardized sequence of a video hook, direct instruction, and retrieval practice where teachers can automate the process of learning, safely aiming to preserve their students' fragile cognitive capacities for the heavy lifting of scientific inquiry.

5.3. Policy Implications for Educational Authorities

On a systemic level, these conclusions challenge the prevailing narrative driving many national and international technology integration policies. Currently, educational authorities frequently equate the sheer volume of classroom digitization with pedagogical progress. Yet, our empirical evidence suggests that uncalibrated technology integration can actively impair learning in complex subjects.

Funding and policy directives need to shift away from the mere accumulation of hardware and screen time toward cognitive-load-optimized instructional design. As generative AI tools like Google Veo become increasingly accessible to localized school districts, curriculum developers require specialized training to identify and eliminate seductive details from official learning materials. Educational media must be vetted not for its entertainment value or production quality, but for its strict adherence to cognitive psychology principles, ensuring that visual segmenting, signaling, and coherence are prioritized.

This paradigm shift must also extend deeply into teacher training programs. Today's educators are navigating a classroom environment shaped by the rapid digital consumption patterns of modern students. Consequently, professional development must move beyond basic Technological Pedagogical Content Knowledge (TPACK) (Mishra & Koehler, 2006) to place a heavy emphasis on Cognitive Load Theory (Sweller et al., 2019) and the neurological impacts of modern digital media consumption habits. Teachers need to be equipped not just with the technical skills to generate engaging media, but with the psychological insight to recognize when a student's working memory is saturated, ensuring they know exactly when it is pedagogically necessary to turn the screens off.

Within the localized context of the Maldivian educational framework, and for similar regional institutional settings, these findings suggest that curriculum developers should exercise caution when integrating digital supplementary materials. While contemporary educational goals increasingly advocate digital literacy, the push for multimedia integration must be balanced with a practical understanding of adolescent cognitive architecture. Institutional policymakers and local curriculum developers are encouraged to evaluate digital supplementary materials through the lens of cognitive load before widespread classroom deployment. By considering established multimedia principles—such as segmenting and coherence when selecting educational media, local authorities can better ensure that artificial intelligence serves as a pedagogical scaffold rather than an unintended cognitive barrier, particularly for students who may be susceptible to modern attentional fatigue.

5.4. Conclusion

Fulfilling the ambitious goals of modern science curricula which demand analytical inquiry, critical thinking, and abstract problem-solving ultimately requires a deep respect for the biological limits of human cognition. The integration of Artificial Intelligence and advanced multimedia into the classroom is not a panacea for the educational challenges posed by the digital age; rather, it is a highly volatile catalyst that must be wielded with precision. This study demonstrates that the success of AI-generated instructional media is not determined by its visual fidelity or entertainment value, but by its strict alignment with the baseline academic load of the

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learner. When applied to foundational, low-interactivity concepts, targeted multimedia can successfully break through the apathy often associated with modern digital media habits, acting as a powerful motivational anchor. However, when deployed amidst the high intrinsic cognitive load of complex abstract science, the observed decline in immediate retrieval scores indicates that the very same media may overwhelm working memory capacity. In these high-load environments, we hypothesize that the visual elements function as seductive details that obstruct schema acquisition. Ultimately, the future of science education does not lie in competing with the rapid-fire entertainment of the internet, nor does it require a wholesale retreat to archaic didactic methods. Instead, it demands a disciplined, evidence-based pedagogy one that meticulously manages students' finite working memory to foster enduring, meaningful scientific literacy.

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