INCORPORATING LEARNING SCIENCES' BEST PRACTICES INTO STEM COURSEWARE

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Abstract

Pedagogy and learning content designers often struggle to sufficiently implement learning science principles that have the potential to make learning more efficient. A few of these principles include managing cognitive load, connecting new information to existing knowledge, and providing timely and explicit feedback. The principles are rarely disputed. The question is not if they should be implemented, but rather how to implement them in learning design and online learning environments in particular.

In this paper, we demonstrate how one STEM courseware provider has implemented these principles in an intentional framework to achieve student-focused, minimalistic, and interactive materials that have exceeded expectations for student engagement and satisfaction. We consider established e-learning principles to showcase the efficacy of this innovative pedagogical framework for online digital content. In particular, we evaluate the framework against Mayer's Principles of Multimedia Learning that show how to optimize learning through the lens of the cognitive theory of multimedia learning. Our framework makes learning easier and more enjoyable by optimizing cognitive load and cognitive processing demands using Mayer's multimedia, coherence, signaling, redundancy, contiguity, segmenting, and pretraining principles. We delineate how these principles are implemented to make an impact on student learning.

Under this framework, we report high engagement in engineering courseware, with > 80% average reading rates across four different Engineering titles assigned in courses. For computer science titles, we report that students read shorter passages (200 words or less) at about 200 words per minute, which is a typical rate, but for longer passages (600+ words), the rate increased to about 800 words per minute, suggesting skimming rather than reading. When using this framework, attrition in one math course was reduced from 17.5 to 4.7%, and the fail rate in one CS course was reduced from 22% to 9%. Several studies show improvement in student grades as a result of using this courseware.

We expand on these research findings and more within the engineering, math, and computer science disciplines highlighting the positive impact of this framework on student engagement, student attrition, learning outcomes, and student satisfaction. Limitations in the current framework and additional opportunities for improvement are discussed.

Keywords: pedagogy, learning science, multimedia learning, higher education, courseware, STEM

1 INTRODUCTION

Learning science has helped the education community understand how people learn and has uncovered principles to make learning more efficient. These principles are rarely disputed. The question is not *if* they should be implemented, but rather *how* to implement them in context. Richard Mayer, one of the most prominent educational psychologists and researchers of our time, proposes principles that optimize learning from the lens of the Cognitive Theory of Multimedia Learning. The Cognitive Theory of Multimedia Learning asserts that:

- Knowledge construction occurs by active processing through dual channels (pictorial and verbal).
- Cognitive resources are limited.
- Learners must attend to or select information, organize that information, and integrate the information multimodally and with other knowledge.

Three types of processing make use of learners' limited cognitive capacity: extraneous, essential, and generative processing [1,2]. Extraneous processing refers to the cognitive processing of material that is not essential for learning the concepts in a lesson [3]. To optimize learning, extraneous processing should be minimized. Essential processing is where essential material is represented. To optimize learning, essential processing should be made manageable using strategies mentioned later, such as breaking complex concepts into smaller learning chunks. Finally, generative processing is where

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learners integrate and make sense of the material being learned. To optimize learning, generative processing can be bolstered by increasing students' motivation and engagement [4]. Structuring the learning experience to optimize the balance between these processing types can make learning easier and more enjoyable.

A general understanding of Mayer's Principles of Multimedia Learning is essential to appreciate zyBooks pedagogy. The Principles of Multimedia Learning discussed in this paper are shown in Table 1. Robert Gagne's Events of Instruction, a 9-step plan for addressing the mental conditions of learning, is also influential in zyBooks' pedagogy [5].

Table 1: Selected Principles of Multimedia Learning

Principle	**Explanation**
Segmenting	Content should be presented in chunks and users should control the lesson's pace
Pretraining	Key terms and concepts should be defined before discussing processes
Signaling	Cues that direct learners' attention should be used
Contiguity	Corresponding words and pictures should be presented near each other on the screen
Coherence	Extraneous material should be excluded
Multimedia	Words and pictures should be used instead of words alone

We describe a framework that is exceptional in facilitating easier and deeper learning for STEM students due to its adherence to seminal learning principles. This paper aims to demonstrate how zyBooks' content delivery approach incorporates the best practices in learning sciences to advance student learning.

2 ZYBOOKS PEDAGOGY

2.1 What are zyBooks?

A zyBook is digital STEM courseware designed to be student-focused, minimalistic, and interactive. To this end, zyBooks uses a simple framework for content delivery - Say, Show, Ask. The Say, Show, and Ask components collectively make up a subsection and are meant to be completed in 5-10 minutes.

The Say component is a concise lead-in to a topic, typically consisting of about 100 words. Next, students encounter the Show component, which teaches through visuals, usually animations. The final component, Ask, is a set of 3-7 learning questions. The purpose of Ask is formative, interactive reading.

While Say-Show-Ask is used for content delivery, Challenge Activities (CAs) and lab assignments are used for assessment. A CA is a mastery-based, algorithmically generated assessment with scaffolded levels.

2.2 Student-focused

2.2.1 Right-sized chunks

Mayer's Segmenting Principle advises breaking the essential content down into chunks. Breaking down the content helps manage essential processing by allowing students to consolidate individual concepts and relationships without overloading cognitive resources [6]. A meta-analysis showed that segmentation applied in multimedia lessons in various domains yielded a median effect size of .79 over ten experiments, each reporting significant results [7].

zyBooks' applies Mayer's Segmenting Principle through short subsections. zyBooks' subsections are designed to be completed in about 5-10 minutes, which is a natural way to segment content into right-sized chunks. These short segments provide natural breaks in the material so students can take a break or move to the next segment.

2.2.2 Integrating new information

Mayer's Pretraining Principle asserts that learners will perform better if they understand the names and characteristics of key concepts before advancing to more complex information. This helps beginners manage the processing of complex material by limiting the amount of essential information needed to retain at once. Once learners fully understand a concept, they can build upon that to create larger mental models that integrate into a wider framework. A meta-analysis found an average effect size of .75 across 16 studies, 13 of which reported significant results [7].

Unfortunately, teachers often "overestimate students' prior knowledge and thus build new knowledge on a shaky foundation" [8]. In Gagne's Events of Instruction, stimulating memories of prior learning is recommended before presenting new content. Thus, during the prewriting phase, zyBook authors carefully consider content sequencing. An author's outline is reviewed by other subject matter experts to create optimal segment sequences.

zyBook authors use analogies, concept maps, exercises, and examples to explicitly highlight connections between new and old information. Researchers have found that students who were presented with definitions and concrete examples performed better than students who only studied definitions [9].

Besides carefully selected content, the zyBooks platform supports knowledge integration by allowing keyword searches and in-text links to previous figures, tables, examples, or equations.

2.2.3 Gaining and maintaining learners' attention

Gagne notes that piquing a student's interest and motivation to learn is paramount because, without stimuli, brain receptors are inactive. Also, adult learners must understand why the content is relevant [10].

In a zyBook, authors attempt to gain students' attention by asking thought-provoking questions, presenting startling facts, or telling stories. In the Say component, zyBook authors attempt to answer "What" and "Why" questions. *What* am I going to learn? *What* is a high-level overview of the concept? *Why* is this concept relevant? *Why* should I care? Further, zyBook authors attempt to keep students engaged through real-life examples. This practice is aligned with Gagne's position that instructors should use varied examples, increasing engagement and enhancing knowledge transfer to unique situations.

2.2.4 Directing attention

Mayer's Signaling Principle encourages highlighting relevant material to guide the learner. This includes using font style and size, arrows, headings, white space, and other spatial cues to direct attention. Research shows that signaling can help improve learning [11-13]. Although Gagne does not use the term "signaling," he also notes the importance of using physical arrangement and highlighting features to facilitate the perception of essential features.

Mayer's Contiguity Principle states that words and corresponding graphics should be near one another. For example, graphics and the text describing them should be visible at the same time (i.e., not on separate pages). This reduces extraneous processing by eliminating the burden on the learner to determine which words relate to which graphics. Freeing learners of this burden allows more cognitive capacity for mentally organizing and integrating the material [14]. A meta-analysis summarizing 22 experiments found a median effect size greater than 1, highlighting the strong benefits of contiguity [2].

zyBooks authors use both the Signaling and Contiguity Principles when designing content. Animations include visual cues such as movement, resizing, recoloring, and unveiling to show relationships, depict motion, and highlight content. Captions appear simultaneously with each animation step. Keywords are formatted using bold and italics and monospace font is used to represent computer code. Feedback for correct and incorrect answers to learning questions is placed close to the wrong answer.

2.2.5 Self-paced

Self-paced materials are student-focused. Gagne points out that both slow and fast learners benefit from self-paced learning [5]. Slower students can spend extra time on the material without the pressure to go to the next lesson. Conversely, faster learners won't get bored and can take on more challenging material faster.

zyBooks lessons on the whole are self-paced. Additionally, within animations, start, pause, and next buttons and a 2x speed setting allow students to study an animation at their own pace. As students complete activities, the platform indicates completion with a checkmark so students see their progress.

2.2.6 Feedback

Feedback must be explicit, and should fully explain what is wrong and how to correct the error. Gagne recommends that instructional designers suggest a line of thought rather than directly giving away an answer. Allowing the student to discover an answer with guidance can lead to more permanent learning [5].

To maximize feedback, zyBook authors are encouraged to use multiple-choice questions, spanning the levels of Bloom's Taxonomy. Question feedback purposefully addresses common student misconceptions and errors, which authors identify during the prewriting phase. Students receive feedback for both correct and incorrect answers and all feedback is explicit. A zyBooks student would never get feedback saying, "That's right. Good job!" or "Not quite. Try again." Instead, feedback is customized to the correct answer and every distractor. These explanations give clarity on why an answer is right or wrong. In a survey with 1,383 respondents, 85% of students agree or strongly agree that they learn a lot from the multiple-choice feedback.

Feedback also must be timely. Students often complain that instructors are too slow in returning assignments so they cannot apply the feedback to the next assignment. Corrective feedback is most useful when the mistake is made so errors do not perpetuate and so students do not get frustrated. zyBooks feedback is auto-generated and immediate.

2.3 Minimalistic

2.3.1 Minimal text

Mayer's Coherence Principle states that any material that does not support the instructional goal should be omitted. Reducing extraneous material allows more processing capacity for essential content. Including funny stories or facts that are tangentially related to the material can be tempting, but if learners are overloaded with extraneous information, they struggle to successfully organize and integrate the core material, leading to frustration and disengagement. Research has shown that including extraneous wording for interest [15-17], expanding on key ideas of the lesson [18,19], and unneeded technical details [20,21] can all hinder learning. The same goes for graphics - funny graphics can be tempting, but they do more harm than good. Extraneous graphics can distract students from essential content or disrupt the process of integrating relevant information because the irrelevant material is in the way [22-24].

Text is aggressively minimized throughout zyBooks, but especially in the Say component, which is limited to about 100 words or 1-2 paragraphs. Minimal text ensures that students spend only a little time reading, which is a less desirable, passive learning activity. In our survey, 81% of students agree or strongly agree that the concise text was very helpful to their learning.

2.3.2 Simplicity

A concept related to Mayer's Coherence Principle is simplicity. In a zyBook, text is minimized, and short, simple words are used rather than verbose language. Terms are always used consistently; synonyms are not allowed. Definitions are written in plain language. Further, when numbers illustrate a concept, simple round numbers are selected if possible. All of these characteristics enhance readability.

Authors also simplify visuals. Visuals are stripped of extraneous detail so students can focus on the visual's important aspects. Icons are frequently used instead of photographs or elaborate drawings. Decorative images are never used; every image must have a pedagogical purpose. Animations and figures are simple, easy to understand, and only include integral information.

2.3.3 Intuitive navigation and organization

Unnecessarily complex navigation and organization are a distraction from learning [25]. Students expend fewer cognitive resources when navigation and organization are intuitive. zyBooks has a minimalist design with no fluff. Each section is a separate webpage, and navigation between sections is simple. A table of contents also allows students to navigate to any section, and the content explorer mode enables searching and filtering. Activities include completion markers which enable easy tracking as a student completes them.

2.4 Interactive

2.4.1 Active learning

Student engagement is regularly cited as a problem, especially in post-pandemic times. According to Wiley's 2022 State of the Student Report, "more than half (55%) of undergraduates admit they’re likely to struggle with staying engaged and interested in their classes."

Their struggle may be related to cognitive overload. Walls of text can overload the working memory's limited capacity. However, active learning can help to engage students by keeping information in short-term memory longer and increasing the chances of information being stored in long-term memory [26].

The "Ask" component of a zyBook consists of questions meant to replace less effective passive reading. Questions often involve engaging, real-life situations. Since each subsection is only about 5-10 minutes long, students engage frequently. In the survey, 87% of students agree or strongly agree that they find the learning questions very helpful.

2.4.2 Multimedia

Generally, using more than one type of media is more effective than using just one type [27-28]. Mayer's Multimedia Principle asserts that multimedia promotes active learning by cueing learners to mentally represent concepts both verbally and graphically and integrate those modality-specific representations into a multimodal conceptual representation. This meaningful integration, enacted through generative processing, increases understanding and knowledge transfer. Across 11 different studies that spanned numerous disciplines, students who learned through multimedia instruction performed 55-121% better on knowledge transfer tests compared to students who learned through a single modality [29-31].

Animations can positively impact learning when created carefully. Animations that explicitly show dynamic changes may lower a student's need to make inferences, thereby reducing the cognitive load [32]. Further, cognitive load can be managed when the student controls an animation's pace and information is chunked into pieces small enough for a novice to understand [33,34].

zyBooks leverages multimedia's power through extensive use of animations. zyBooks' animations consist of 3-5 steps with each step lasting only 5-7 seconds. These small segments ensure students' cognitive processes are manageable. Only essential information is included to limit distraction or confusion. Students control an animation's pace with options to view at normal or 2x speed and pause at any time. In the survey, 77% of students agree or strongly agree that the animations helped them understand the material.

3 RESULTS

3.1 Student Performance

One large online university introduced the quantitative reasoning zyBook into two of its courses as a part of a shift toward theory-based practices in education [35]. This shift resulted in an attrition drop from 17.5% to 4.7% in one course, and from 13.9% to 4.0% in another. The university then extended the framework to six additional courses, all of which saw similar drops in attrition (Table 2).

Table 2: Attrition rate before and after feature changes. Number of students in parentheses.

	Before changes	After changes
Intro College Algebra	21.7% (1652)	10.7% (1594)
College Algebra	17.2% (1538)	9.9% (1472)
Calculus 1	36.2% (116)	10.5% (114)
Calculus 2	23.1% (26)	10.5% (19)
Statistics 1	16.9% (195)	10.6% (151)
Statistics 2	23% (61)	15.3% (72)

Numerous studies have shown an increase in student performance with zyBooks. In 2015, four introductory computer programming courses at three research universities switched to using a zyBook in their courses [36]. For each, two course offerings were compared, the first using a static textbook or static web resources, and the second using the zyBook. Across all courses, involving 1,945 students, course grades improved by 0.28 points on a 0-4 point scale, or 1/4 letter grade, from static to interactive textbook. More importantly, students in the lower quartile of the course improved by 0.38 points, or 1/3 letter grade. Exam scores improved by 13.6% and project scores by 7.4%. Figure 1 shows the grade distributions for each of these four courses before and after introducing the zyBook.

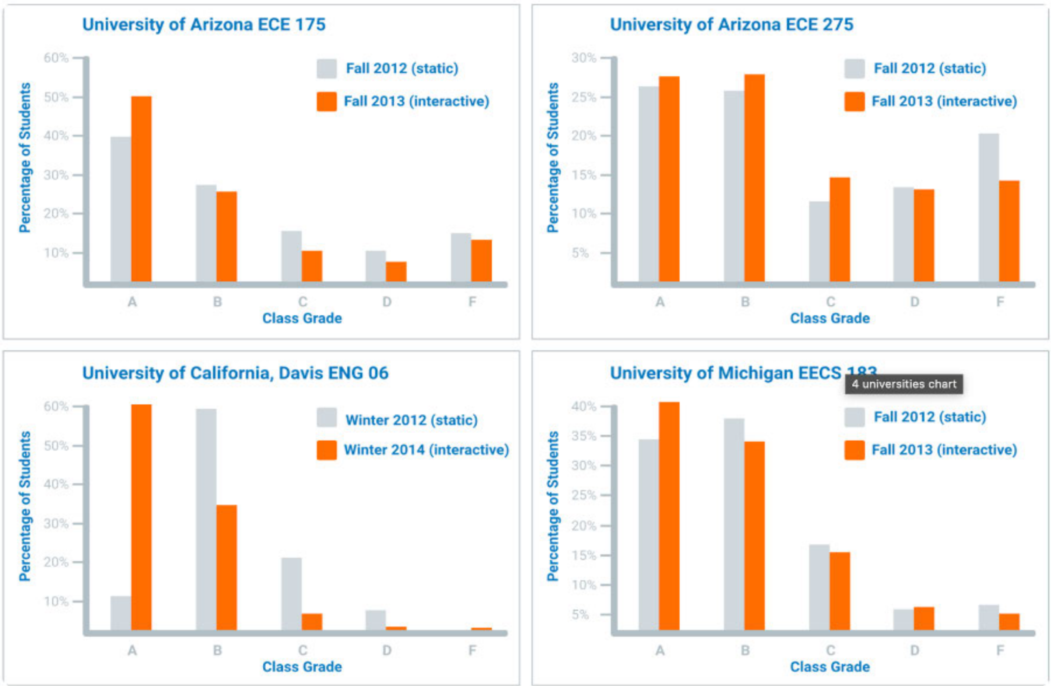

Figure 1. Course grade improvements across four different courses after switching to zyBooks.

In a follow-up study, one of the instructors taught an earlier CS0 course. Compared to the passive textbook, the class using the zyBook saw their pass rate increase from 78% to 91%, and an increase in average course grade from 84 to 87 [37]. In 2023, another large online university introduced zyBooks into their introductory computer science course and measured student outcomes. Withdrawal and fail rates dropped substantially and the proportion of students achieving a course grade of C or higher increased from 76% to 91% [38].

3.2 Minimalism and engagement

In a recent study, zyBooks' research team looked at the student reading times for content in 12 courses using three different computer science zyBooks [39]. For one of the texts, written in a non-concise style, students read shorter passages (200 words or less) at about 200 words per minute, which is a typical rate. But for longer passages (600+ words), the rate increased to about 800 words per minute, suggesting skimming rather than reading (Figure 2 left). For another text, written in a concise style with text passage sizes kept below 250 words, students spent more time (around 200 words per minute) reading the text passages, and their time spent was well correlated with text length, suggesting students were carefully reading rather than skimming (Figure 2 right). In this case, less appears to be more.

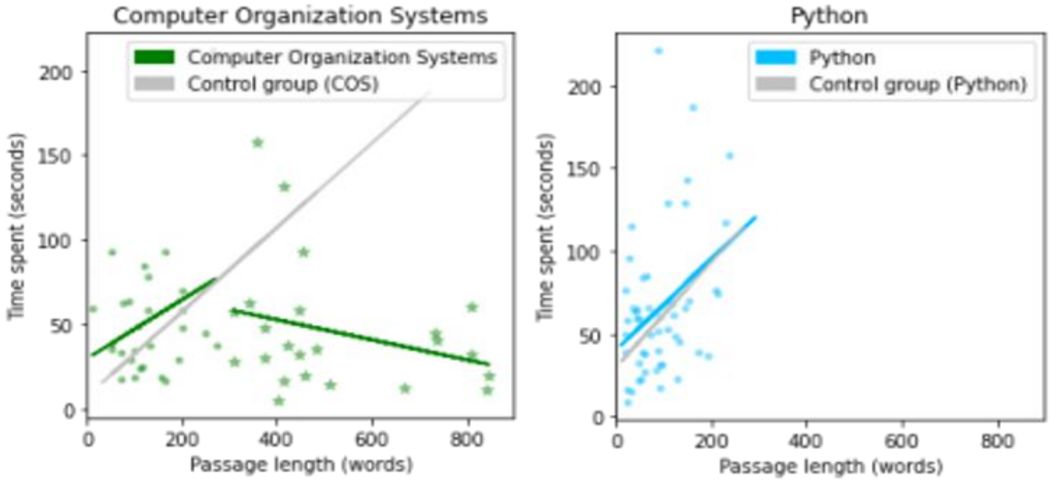

Figure 2. (Left) Time spent reading passages in a non-concise book. Regression lines are for under and over 200 words (Right) Time spent reading in the concise book.

3.3 Interactivity and engagement

An engineering instructor using the Material and Energy Balances zyBook reported across seven cohorts (> 600 students), that median reading participation was over 93% across all cohorts [40]. Furthermore, auto-graded homework assignments were correctly completed at a rate of 91% - allowing unlimited attempts and showing feedback on the formative assignments allowed students to persist until they understood and could solve the assignment (Figure 3).

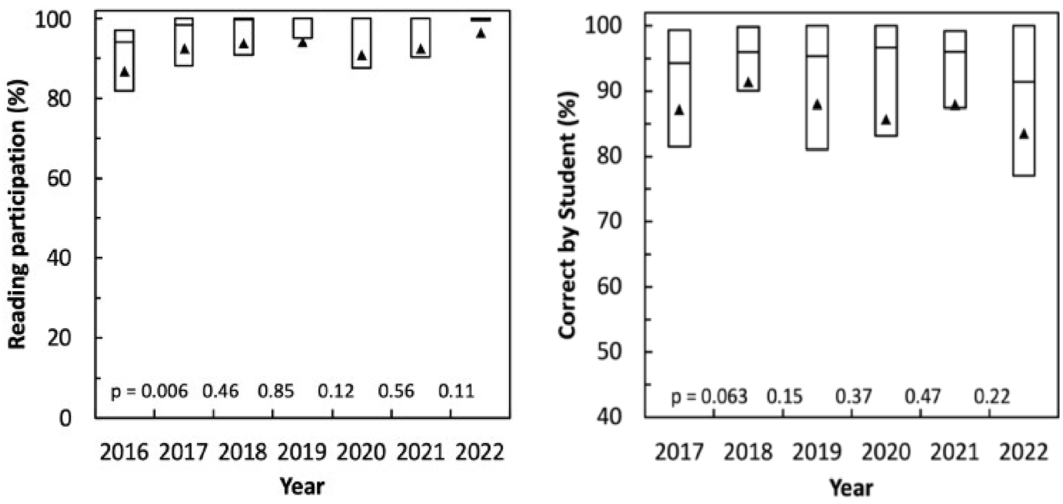

Figure 3. (Left) Reading participation rates over 7 cohorts in Material and Energy Balances zyBook. (Right) Correctly completed homework assignments across 7 cohorts.

In another study, the authors measured student engagement through activity completion percentage and found a significant positive correlation between student engagement and the percentage of final course grades awarded for the completion of assigned activities [41]. Assigning any percentage at all corresponds to over a 35% increase in content completion, and the higher the assigned percentage, the greater the completion increase. (Figure 4).

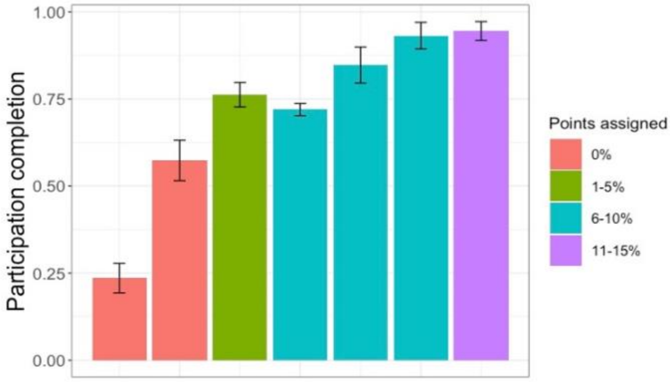

Figure 4. Mean percent activity completion and standard deviations for courses using the Material Science textbook, grouped by the number of points assigned for activity completion.

For a 300+ student CS1 class, several behaviors (e.g., completing activities) were identified that are good at predicting poor performance on the midterm exam and class grade [42]. A linear model was developed combining the behavioral variables in Weeks 2-4 to predict the Week 6 midterm exam score. This model achieved 91% accuracy for students' midterm scores.

4 CONCLUSIONS

zyBooks courseware implements seminal learning principles in a student-centered, minimalistic, and interactive experience. Research has shown a positive impact of zyBooks' framework on students' performance, learning, and engagement. These studies highlight the effectiveness of designing a learning framework guided by learning principles and with the cognitive theory of multimedia at the core. Segmenting, pretraining, signaling, and contiguity promote a student-centered learning experience that minimizes confusion and keeps students on track. Coherent text prevents students from getting lost in the excess. Multimedia content enhances learning by extending it across cognitive processing modalities.

The majority of research on zyBooks efficacy has been conducted in computer science courses, with some exceptions. More research is needed to compare the efficacy of zyBooks among more disciplines. Through collaboration with instructors, we plan to expand the research scope.

Improvements to zyBooks platform, content, and framework are always ongoing and informed by research efforts. An opportunity to add narration to animations in addition to written captions is under exploration to support Mayer's modality principle.

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