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## **Cognitive load management: Learning abstract and complex scientific concepts using visual metaphors and metonymies**

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### **ABSTRACT**

This study applies the principles of metaphors and metonymies in visual learning media to manage students' cognitive load and enhance their comprehension of complex scientific concepts, specifically cell biology, in lower secondary education. Using the ADDIE (analysis, design, development, implementation, and evaluation) model, a 2D animated audio-visual learning media was developed and evaluated. The research explored the impact of the developed learning media on intrinsic, extraneous, and germane cognitive loads using questionnaires and pre-/post-tests with 303 participants (science teachers and lower secondary students) from five districts in West Java, Indonesia. Expert evaluations from linguistics, media, and science education specialists were also incorporated. The results indicate that the developed visual media is effective in facilitating information processing and meaning-making, leading to improved comprehension and retention of complex cell biology concepts. The use of metaphors and metonymies helped students connect abstract scientific concepts to familiar contexts, reducing extraneous cognitive load and promoting deeper understanding and concept retention. Overall, the findings suggest that visual media employing metaphors and metonymies can be a valuable tool for teaching highly abstract and complex scientific concepts.

**Keywords:** metaphors, metonymies, visual media, cognitive load, abstract concepts

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### **INTRODUCTION**

In lower secondary science education, teachers often face difficulties in conveying abstract and complex concepts to students, which can result in increased cognitive load (Albus et al., 2021). Cognitive load is defined as the mental burden imposed by a task on the cognitive system (Tabatabaee et al., 2024). According to cognitive load theory, three types of cognitive load are identified: intrinsic cognitive load (ICL), extraneous cognitive load (ECL), and germane cognitive load (GCL). Intrinsic cognitive load arises from the inherent complexity of the task or information itself and is influenced by factors such as individual skill level, the amount of information, and the interrelation of information elements. In contrast, extraneous cognitive load is affected by external factors such as learning strategies, instructional design, and teaching techniques (Kala & Ayas, 2023). Germane cognitive load refers to the mental effort required for schema construction as information is transferred from working memory to long-term memory (Fox & Rey, 2024). This definition implies that some information is inherently more difficult to comprehend than others, emphasizing the importance of adapting instructional approaches to the complexity of the content to support effective learning.

Within the context of information processing in learning, highly complex and abstract information is known to generate a high degree of cognitive load (Hery Murtianto et al., 2022), which can directly hinder learning. Excessive cognitive load occurs when the demands of learning exceed the limited capacity of working memory (Fox & Rey, 2024). When working memory becomes overloaded, students frequently report feelings of being “overwhelmed,” “confused,” and “unable to keep track of information” (Jordan et al., 2020; Tarng et al., 2022). For this reason, effective management of cognitive load is essential to ensure that sufficient mental effort is allocated to understanding complex information rather than being burdened by poorly designed instruction. Recent studies in cognitive neuroscience have emphasized that appropriate cognitive load management prevents cognitive overload and reduces stress, confusion, and poor performance (Tarng et al., 2022), thereby minimizing distraction and promoting higher-quality learning (Baranowska, 2021).

Nevertheless, complex scientific concepts pose a considerable challenge for learners due to their abstract nature and limited connection to students’ everyday experiences (Favela & Amon, 2023; Jordan et al., 2020). In addition, science topics are often dense with specialized terminology that is unfamiliar to students, requiring greater mental effort to achieve comprehension (Yun, 2021). Abstract scientific concepts generate particularly high intrinsic load due to element interactivity—the number of elements that must be processed simultaneously in working memory to understand a concept (Kala & Ayas, 2023). For example, understanding cellular respiration requires students to simultaneously integrate information about multiple organelles, chemical reactions, energy transformations, and their interconnections. For this reason, previous studies have developed various strategies to manage learners’ cognitive load using pictures, graphs, and diagrams to support visualization and information processing, as well as using interactive and adaptive learning technologies (Bravo & Bohemia, 2021; Pettersson et al., 2020; Paas & van Merriënboer, 2020). These developments highlight the potential of visualization as an effective medium for delivering science content in ways that facilitate cognitive load management and improve learning effectiveness.

Furthermore, several instructional strategies have been introduced to assist learners in managing cognitive loads associated with abstract and complex concepts. These include eliminating non-essential information, providing clear and relevant illustrations or diagrams, and offering simplified explanations (Hogan & O’flaherty, 2021; Kerzel & Andres, 2020; Susilaningsih et al., 2019). The importance of effective and contextualized illustration has also been emphasized (Maxcey et al., 2020; Shimizu et al., 2021). Moreover, the use of digital technologies such as virtual reality and augmented reality has been recommended as an effective approach to support conceptual understanding (Agbo et al., 2023; Su et al., 2023).

Considering these strategies and methods, this study explores the novel use of visual metaphors and metonymies, combined with contextual illustration, to enhance engagement and comprehension of complex scientific concepts. This approach is based on findings that visual metaphors and metonymies are effective tools for increasing student involvement and engagement, facilitating comprehension of abstract concepts, and improving learning outcomes (Purcell, 2018). Students using visual metaphors have reported that concepts have become clearer, more relatable, and easier to remember compared to traditional text-based instruction (Hanif, 2020; Zhang & Dolah, 2024). These findings suggest that the use of visual metaphors and metonymies enhances comprehension and supports working memory during the learning process. This is because metaphors help contextualize abstract and complex concepts, enabling easier schema construction and more efficient transfer of information to long-term memory (Bearman & Ajjawi, 2021; Rajsic et al., 2020), which ultimately leads to improved learning and retention.

The use of visual metaphors and metonymies has been applied in various disciplines, including mathematics (Doğan & Sönmez, 2019; Retnowati et al., 2018; Sugiman et al., 2019), language studies (Neal-Smith et al., 2023; Veliz & Véliz-Campos, 2022), music (Hsu & Chiang, 2022), and advertising studies (Margariti et al., 2022). These studies demonstrate that metaphor-based audio-visual media are perceived as more engaging and stimulating for students, fostering greater interest and encouraging creative thinking, which contributes to deeper comprehension (Hanif, 2020; Moya Guijarro, 2019). However, the development of visual media to effectively

convey complex and abstract information must be supported by a thorough understanding of the content complexity and by appropriate instructional strategies for integrating such media into the learning process (Ismaeel & Mulhim, 2021). Despite evidence supporting the effectiveness of visual metaphors and metonymies in learning, their impact on the delivery of scientific concepts remains underexplored, particularly in lower secondary contexts. Previous studies have primarily focused on how visual media facilitate comprehension and interest, without sufficiently examining their influence on learners' cognitive systems, including intrinsic and extrinsic cognitive loads, in processing complex information.

While previous studies have demonstrated the effectiveness of visual metaphors and metonymies in facilitating student comprehension and interest, limited research has examined their influence on learners' cognitive systems, specifically on intrinsic, extraneous, and germane cognitive loads when processing complex information. Moreover, few studies have investigated how the combination of visualization principles and digital technology can be systematically designed to meet the diverse cognitive needs of students. This gap is particularly evident in the context of learning abstract biological concepts in lower secondary schools, where cognitive load management is critical but rarely addressed through metaphor-based visual interventions.

To address the gap identified above, this study investigates the following research questions: (1) How effective are visual metaphors and metonymies in managing students' cognitive load when learning cell biology concepts? (2) What is the specific impact of metaphor-based visual media on intrinsic, extraneous, and germane cognitive loads? (3) How does the use of visual metaphors and metonymies influence students' concept mastery and long-term retention of complex scientific concepts?

## **METHOD**

This study utilized the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) to develop and test a metaphor-based visual learning media. The process began with a literature review, followed by product development, classroom implementation, and evaluation using a quasi-experimental design (Sofyan, 2019). The research questions were systematically addressed as follows: RQ1 (effectiveness on cognitive load management) was investigated during the Evaluation stage using cognitive load questionnaires. RQ2 (specific impact on intrinsic, extraneous, and germane loads) was answered through expert validation in the Development stage and comparative analysis of experimental and control groups in the Evaluation stage. RQ3 (influence on concept mastery and retention) was addressed through correlation analysis conducted during the Evaluation stage. The five stages of the ADDIE model are described in detail below.

Analysis stage needs assessment was conducted through curriculum review and interviews with teachers and students to identify abstract cell biology concepts requiring visualization and to select appropriate metaphors and metonymies. Design stage; A storyboard was developed outlining the media structure, content selection, and visual delivery of metaphors and metonymies aimed at reducing cognitive load. Development stage: A 2D animated video employing the "factory of life" metaphor was created. Expert validation from media, linguistics, and science education specialists yielded "Excellent" ratings (80.2%, 80.5%, and 80.0%, respectively). Revisions were made based on expert, teacher, and student feedback. Implementation stage: The media was tested in classrooms using a quasi-experimental design with control and experimental groups to evaluate its effect on cognitive load management. Evaluation stage: Data from questionnaires, pre-tests, and post-tests were analyzed to assess the media's impact on students' cognitive load and concept mastery.

### **Participants and Instruments**

A total of 303 participants were involved in the trial of the visual media during the development and implementation phases. The development phase comprised 21 science teachers and 46 students, while the implementation phase included 5 science teachers and 246 lower secondary students drawn from five districts in West Java, Indonesia. Participants were selected

using purposive sampling based on the following criteria: (1) student participants were Grade 8 students who had not previously studied cell biology in their curriculum; (2) schools had adequate technological infrastructure, including projectors and audio systems; (3) science teachers demonstrated willingness to participate and received training on media implementation; and (4) schools represented diverse socioeconomic backgrounds to ensure generalizability. Each district contributed one school, and within each school, students were randomly assigned to either the experimental or control group to minimize selection bias. All students were native Indonesian speakers with comparable prior academic achievement in science (mean Grade 6 science scores: experimental group = 75.3, control group = 74.8; no significant difference,  $p > 0.05$ ).

Data collection employed several instruments tailored to each stage of the research, with specific administration protocols described as follows. In the Analysis stage, interviews were conducted with 10 teachers and 20 students (30–45 minutes each) to identify the types of media needed for learning complex and abstract scientific concepts and to select appropriate visual metaphors and metonymies to visualize the concepts. A checklist was used during the Design stage to ensure the effectiveness of the product design, focusing on media structure, content selection, and the visual presentation of scientific concepts through metaphors and metonymies. The checklist included 25 items rated on a 4-point scale (1 = poor, 4 = excellent), covering visual clarity, audio quality, metaphor appropriateness, and alignment with learning objectives.

In the Development stage, an observation sheet (validation rubric) was used by experts in science learning, media, and linguistics to evaluate the learning content, animation quality, and the appropriate application of metaphor and metonymy principles in the visual media. The rubric consisted of 15–20 indicators for each expert domain, rated on a 5-point Likert scale (1 = very poor, 5 = excellent). Expert validation sessions were conducted individually (60–90 minutes each), followed by revision meetings to discuss suggested improvements. Additionally, focus group discussions with teachers ( $n = 21$ ) and students ( $n = 46$ ) were conducted to gather qualitative feedback on the potential of the media to facilitate cognitive load management.

Three main instruments were developed: (1) a Cognitive Load Management Questionnaire measuring extraneous load, (2) Learning Worksheets measuring intrinsic load, and (3) Pre- and Post-Concept Mastery Tests measuring germane load. All instruments underwent rigorous validation procedures through expert review and pilot testing. An expert panel evaluated the relevance and clarity of each item. The Content Validity Index (CVI) was calculated, yielding values of 0.89 for the cognitive load questionnaire and 0.92 for the concept mastery test, both exceeding the minimum acceptable threshold of 0.80. In the implementation stage, the quasi-experimental method necessitated the use of these three types of instruments.

First, the Cognitive Load Management Questionnaire measured extraneous load using 5-point Likert scales (1 = strongly disagree, 5 = strongly agree). Participants responded to statements such as “The use of metonymy in visual media facilitates recall of cell components and their functions,” indicating their level of agreement or disagreement. The questionnaire was administered immediately after each learning session across all six sessions, and mean scores were calculated for analysis. This questionnaire was validated through Exploratory Factor Analysis (EFA) conducted on pilot data ( $n = 150$ ). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.847, and Bartlett’s test of sphericity was significant ( $\chi^2(105) = 1847.23$ ,  $p < 0.001$ ), indicating suitability for factor analysis. EFA with varimax rotation confirmed a single-factor structure for extraneous load, explaining 61.4% of the total variance. Factor loading ranged from 0.58 to 0.83, with all items loading substantially on the intended factor. All 15 items in the questionnaire demonstrated excellent internal consistency reliability (Cronbach’s  $\alpha = 0.89$ ).

Second, the Learning Worksheets measured intrinsic cognitive load. Students completed three worksheets during the intervention period, each containing 4–5 open-ended tasks requiring the application of concepts to novel scenarios. The worksheets assessed intrinsic load based on students’ ability to process complex information. Tasks included drawing and labeling cell structures using learned metaphors, explaining organelle functions in their own words, and creating new metaphors for cellular processes. The worksheets were scored using analytical rubrics (maximum 100 points each). Expert validation confirmed content validity (CVI = 0.88), and inter-rater reliability between two trained raters was high (Cohen’s  $\kappa = 0.87$ ). Task difficulty

and cognitive demand were calibrated through pilot testing to ensure appropriate measurement of intrinsic cognitive processing.

Third, the Pre- and Post-Tests measured germane load. The tests consisted of 20 multiple-choice questions aligned with Bloom's taxonomy: 8 items at the knowledge level, 7 items at the comprehension level, and 5 items at the application level. The test was validated through expert review (CVI = 0.92) and pilot testing (n = 150), demonstrating strong reliability with a KR-20 coefficient of 0.85. Item analysis indicated appropriate levels of item difficulty (range: 0.35–0.75, mean: 0.58) and discrimination indices (range: 0.30–0.65, mean: 0.48), indicating that the items effectively differentiated between high and low achievers. The pre-test was administered one week before the intervention, and the post-test was administered one week after the intervention concluded.

Prior to implementation, the five participating teachers attended a one-day training workshop (6 hours) covering: (1) principles of cognitive load theory; (2) effective use of visual metaphors in teaching; (3) technical operation of the media; (4) classroom management strategies; and (5) data collection procedures. Teachers received a detailed implementation manual with lesson plans for each session. Implementation fidelity was monitored through classroom observations and teacher self-report logs.

### **Data analysis**

Quantitative data were analyzed using SPSS version 26.0 with a significance level set at 0.05. Independent samples t-tests were employed to compare the experimental and control groups on intrinsic and germane cognitive loads, while chi-square tests were used for extraneous load (categorical data). Effect sizes were calculated using Cohen's d for t-tests and Cramér's V for chi-square tests. A one-way ANCOVA was conducted on post-test concept mastery scores, with pre-test scores as the covariate to control for initial differences. Pearson correlation analyses examined the relationships among the three cognitive load components. Prior to analysis, data were screened for normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene's test).

Data from expert judgments and participant questionnaires were analyzed descriptively using percentages. Average percentage scores were calculated using the formula (1).

$$RS = \frac{f}{n} \times 100\% \dots\dots\dots (1)$$

Where: RS = Percentage of responses  
f = Total scores for each sub-variable  
n = Total maximum score

and interpreted based on established criteria: Excellent ( $X > 76$ ), good ( $50 < X \leq 75$ ), poor ( $25 < X \leq 50$ ), and very poor ( $X \leq 25$ ) (Sofyan, 2019).

## **FINDINGS AND DISCUSSION**

### **Findings**

This study aimed to develop visual learning media predicated on the principles of metaphor and metonymy to manage students' cognitive load in the context of science education. Following the five phases of the ADDIE model, the study produced: (1) an audio-visual animation addressing cell biology concepts at the lower secondary level; (2) evaluations provided by three experts specializing in linguistics, media, and science education; (3) assessments of the media conducted with 21 science teachers and 46 students; and (4) a trial implementation of the visual media for cognitive load management involving 246 students.

### **Analysis stage**

In the Analysis stage, the study collected data through curriculum identification and through responses obtained from teacher and student participants. The curriculum analysis revealed that cell biology is among the most abstract and terminology-heavy topics in lower secondary science. Consequently, students expressed the need for engaging and accessible

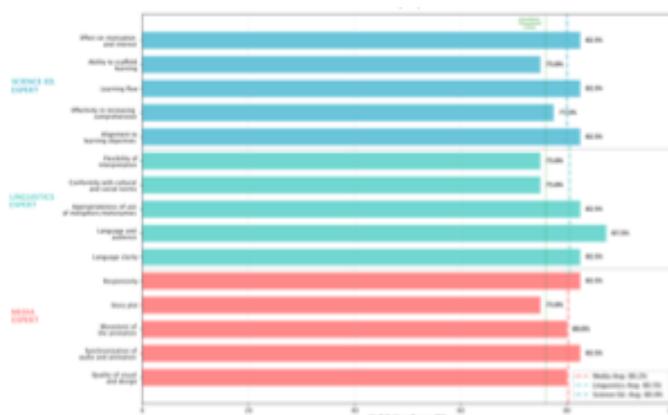
learning methods, while teachers requested guidance on teaching techniques that could help students contextualize abstract concepts. Both teachers and students expressed interest in the proposed visual media designed using metaphors and metonymies to facilitate comprehension of complex scientific concepts. The visual media product, incorporating images, graphs, and animations, was considered beneficial for understanding abstract concepts. Furthermore, the media was perceived as an effective tool to support students' cognitive load management and the retention of learned concepts. The use of metaphors and metonymies also provided a novel learning experience, enabling students to connect complex ideas with familiar concepts and thereby promoting understanding and engagement.

**Design stage**

During the Design stage, the storyboard was developed into a two-dimensional audio-visual animation using animation software. The animation was then edited by adding dubbing and background sound and was rendered using Adobe Premiere Pro, resulting in a two-dimensional animation video in MP4 format with the following specifications: (1) the visual media is compatible with laptops, Android, and iOS devices; (2) the media focuses on the abstract and terminology-heavy concept of cells; and (3) the design of the media employed the “factory of life” metaphor to establish clear connections between familiar objects and cellular processes, as well as metonymic associations such as the “generator” to represent mitochondria, thereby reinforcing real-world connections.

**Development stage**

In the Development stage, the animation underwent expert judgment in three aspects: media, linguistics, and learning content. The results of the expert judgment and the detailed indicators for each aspect are presented in Figure 1.



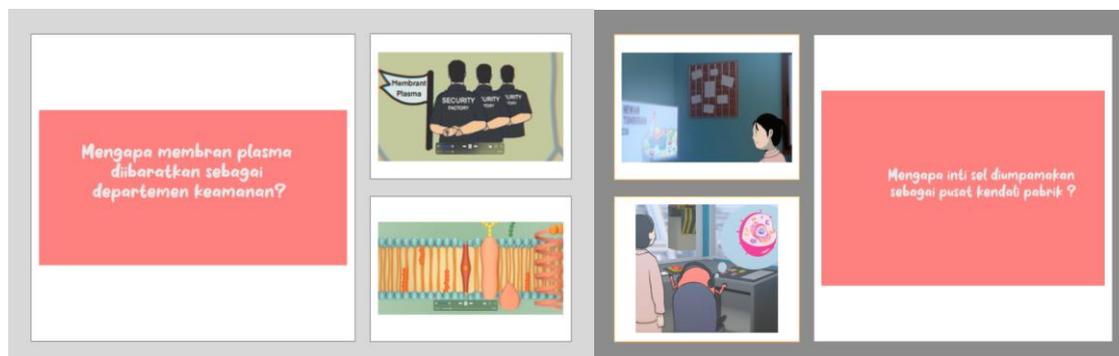
**Figure 1. Expert Validation Result**

The expert judgment from the media, linguistics, and science education specialists yielded average scores of 80.2%, 80.5%, and 80.0%, respectively, all of which fall within the “Excellent” category. In addition to the quantitative ratings, the experts provided valuable qualitative feedback that informed the refinement of the media.

The media expert praised the visual execution but recommended improving the synchronization between narration and animation in Scenes 3 and 5, as well as enhancing the color contrast of the nucleus. The linguistics expert confirmed the cultural appropriateness of the “factory” metaphor for Indonesian students but identified issues related to the rapid introduction of scientific terminology without sufficient scaffolding. The expert suggested adding explanations in Indonesian before transitioning to technical terms and praised the use of concrete metonymic associations, such as the “generator” to represent mitochondria. The science education expert acknowledged the conceptual accuracy of the content but recommended adding guiding questions at three-minute intervals and including a summary segment to maintain student engagement throughout the eight-minute video. All expert recommendations were implemented, substantially

enhancing the pedagogical effectiveness of the media and its readiness for classroom implementation.

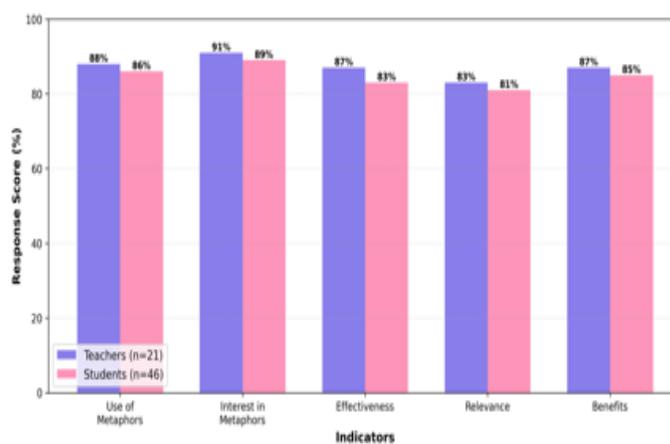
In response to the science education expert’s suggestion, guiding questions were incorporated throughout the video to maintain student engagement with the storyline, as illustrated in Figure 2. These results indicate that the product is suitable for further testing in real classroom settings.



**Figure 2. View of the Visual Media (animation) based on Metaphors and Metonymies**

### ***Implementation stage***

The Implementation stage was the phase in which the product was introduced to the participants of the study to obtain their initial perceptions of its use in a real classroom setting. This stage involved 21 science teachers and 46 lower secondary school students. The respondents participated in a focus group discussion and were given questionnaires regarding the visual media based on metaphors and metonymies. The results of the questionnaire are presented in Figure 3.



**Figure 3. Teachers and Students Respondents' Response on the Use of metaphors and Metonymies in learning about Cells**

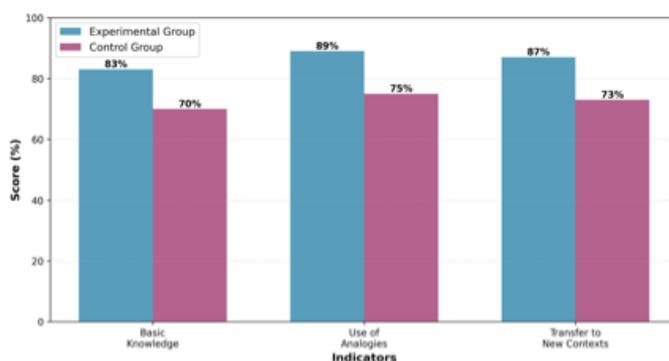
Analysis of the focus group discussions and questionnaire responses led to the conclusion that the implementation of visual metaphors and metonymies within the science curriculum, particularly in the study of cell biology, facilitated a deeper understanding of the topic and increased student engagement. In general, both student and teacher participants expressed positive perceptions toward the use of visual metaphors and metonymies. The participants perceived the visual media product as an effective method for increasing comprehension, interest, and the quality of learning in subjects considered abstract and complex. Consistent with prior research, several studies suggest that the application of metaphors and metonymies offers a valuable approach to understanding the cognitive processes through which students manage complex information, establish connections between interrelated concepts, and develop a robust understanding of subject matter (Bravo & Bohemia, 2021; Brdar & Brdar-Szabó, 2020; Lancor, 2015). The results of the Implementation stage provided a solid foundation for applying the visual

media based on metaphors and metonymies in classroom settings to examine the influence of the media on students' cognitive load management.

**Evaluation stage**

In the Evaluation stage, the visual media was tested on 246 students, comprising 138 students in the experimental group and 108 students in the control group. This trial aimed to analyze the effectiveness of the media in managing students' cognitive load during the learning process. Cognitive load management was analyzed from three aspects: intrinsic load, extraneous load, and germane load. The measurement of intrinsic load, structured through worksheets comprising three indicators, sought to determine the extent to which students were able to process complex and abstract information. The results of the intrinsic load measurement are presented in Figure 4.

The intrinsic load measurement data indicated that the experimental group demonstrated a higher ability to process information compared to the control group across all indicators. An independent samples t-test revealed a statistically significant difference in intrinsic load between the experimental group ( $M = 86.3, SD = 8.2$ ) and the control group ( $M = 72.6, SD = 9.8$ ),  $t(244) = 5.82, p < 0.001$ . The effect size was large (Cohen's  $d = 0.75$ ), indicating substantial practical significance. These findings indicate that the use of visual metaphors and metonymies facilitated students in processing complex and abstract information by enabling them to relate scientific information to more familiar real-life concepts, resulting in more comprehensive understanding, enhanced multidisciplinary thinking, and greater creative thinking. This was evident in students' responses in the worksheets, in which they related the concept of the cell membrane to a "house door" after learning the metaphor of the membrane as a "factory gate" presented in the storyline of the visual media product. Students were not only able to comprehend the concept of the cell membrane within cellular structure but were also able to think creatively and apply the concept to novel situations by generating alternative metaphoric and metonymic examples.

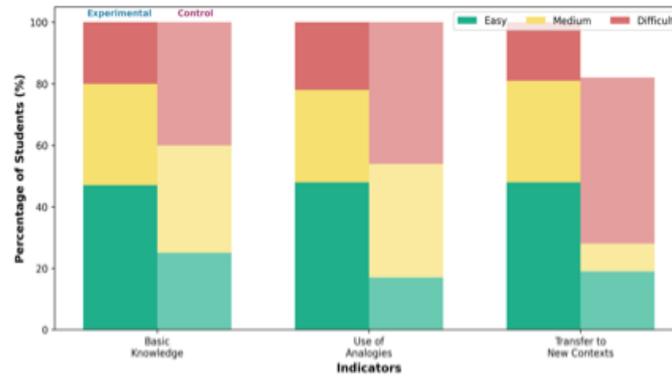


**Figure 4. Intrinsic Load Measurement**

The measurement of extraneous load aimed to obtain information regarding the amount of mental effort exerted by students in understanding a concept. Extraneous load was measured using a questionnaire that recorded the percentage of students' responses regarding their level of difficulty in processing information, based on three indicators presented in Figure 5.

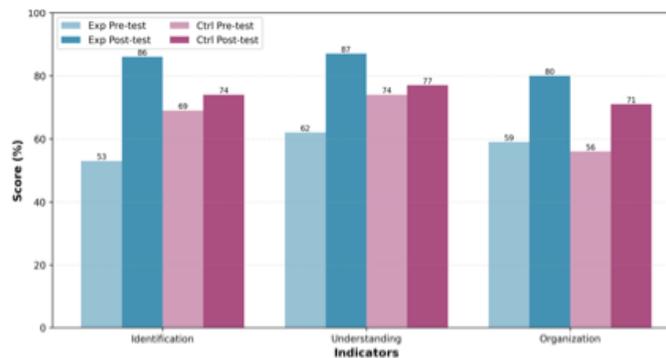
The results of the extraneous load measurement revealed that students in the experimental group experienced lower mental effort in understanding the same concepts compared to those in the control group. A chi-square test of independence showed a significant association between group membership and perceived difficulty level,  $\chi^2(2) = 28.45, p < 0.001$ , Cramér's  $V = 0.34$ . Standardized residuals indicated that students in the experimental group were significantly more likely to report an "easy" level of difficulty ( $z = 3.8$ ) and significantly less likely to report a "difficult" level ( $z = -3.6$ ) compared to those in the control group. The medium effect size indicated a meaningful practical difference in the amount of mental effort required for learning. These findings suggest that the use of visual metaphors and metonymies enabled students to process complex and abstract concepts more effectively while requiring lower levels of mental effort during the learning process. These findings are consistent with previous studies indicating

that the simultaneous use of verbal and visual knowledge representations can reduce extraneous load and improve learning outcomes.



**Figure 5. Data on Extraneous Load Measurement**

In addition to the questionnaires, a pre-test and post-test were conducted to measure students’ concept mastery in order to analyze students’ germane load, which was reflected in their ability to relate newly learned information to knowledge stored in long-term memory. The pre- and post-tests consisted of twenty multiple-choice questions. The results of the tests are presented in Figure 6. An ANCOVA with pre-test scores as the covariate demonstrated a significant main effect of group on post-test performance,  $F(1,243) = 45.67, p < 0.001, \text{partial } \eta^2 = 0.16$ . After controlling pre-test differences, the experimental group (adjusted  $M = 84.3, SE = 0.9$ ) significantly outperformed the control group (adjusted  $M = 74.2, SE = 1.0$ ) on the post-test, with a medium to large effect size indicating substantial practical significance.



**Figure 6. Data of Germane Load Measurement**

These findings suggest that the experimental group achieved a higher level of conceptual mastery. For instance, students in the experimental group were able to accurately identify cellular organelles, describe their functions, and explain the complex interplay among organelles that is essential for cellular viability. Although some improvement was anticipated, the control group continued to struggle to perform these tasks effectively. Additionally, in the organization indicator, students demonstrated the ability to create mind maps that related cell organelles to components of a “factory of life,” applying metaphors and metonymies to represent cellular concepts. These results reveal that the use of metaphors and metonymy is an effective strategy for developing students’ relational thinking through processes of meaning-making and contextualization of information.

To further explore the relationships and interdependencies among the three components of cognitive load, this study employed a correlation test, the results of which are presented in Table 1.

**Table 1. Correlation Test of the Relationship between Components of Cognitive Load**

No	Correlation	Coefficient relation ( $r^2$ )		notes
		Experiment	Control	
1.	Intrinsic load towards germane load	0.785 $r = 0.88$	0.467 $r = 0.89$	$p = 0.00^* < 0.01$
2.	Extraneous load towards germane load	-0.578 $r = 0.76$	-0.676 $r = 0.822$	$p = 0.00^* < 0.01$
3.	Intrinsic load towards extraneous load	-0.735 $r = 0.857$	-0.498 $r = 0.706$	$p = 0.00^* < 0.01$

The results of the correlation analysis indicated that the three components of cognitive load were significantly correlated ( $p = 0.00^* < 0.01$ ). Nevertheless, it is important to note that germane load in the experimental group was predominantly influenced by intrinsic load, whereas in the control group, extraneous load exerted a greater influence on germane load. Pearson correlation analyses were conducted to examine the relationships among the cognitive load components. For the experimental group, intrinsic load showed a strong positive correlation with germane load ( $r^2=0.785$ ,  $p < 0.001$ ), while extraneous load demonstrated a strong negative correlation with germane load ( $r^2=-0.578$ ,  $p < 0.001$ ). Intrinsic and extraneous loads were also strongly negatively correlated ( $r^2=-0.735$ ,  $p < 0.001$ ). In contrast, the control group showed a moderate positive correlation between intrinsic and germane loads ( $r^2=0.467$ ,  $p < 0.001$ ), while extraneous load demonstrated an even stronger negative relationship with germane load ( $r^2=-0.676$ ,  $p < 0.001$ ). These findings suggest that, for the experimental group, concept mastery was primarily driven by effective information processing, characterized by high intrinsic load and low extraneous load. In contrast, for the control group, barriers related to mental effort, reflected in high extraneous load, were the predominant limiting factor for concept mastery.

## Discussion

### *Theoretical interpretation of findings*

The significant improvement in cognitive load management observed in the experimental group can be theoretically explained through the integration of dual coding theory (Costley et al., 2021) and cognitive load theory (Sweller et al., 2019). Visual metaphors and metonymies functioned as dual representational systems that simultaneously activated verbal and visual processing channels. This dual engagement reduced the burden on working memory by distributing cognitive processing across multiple modalities.

More critically, metaphors served as conceptual scaffolds that bridged abstract cell biology concepts with concrete, familiar life experiences. By representing the cell as a “factory of life” and mitochondria as “generators,” the visual media transformed element interactivity, which is the key determinant of intrinsic load. Rather than processing isolated abstract terms, students were able to leverage existing knowledge schemas about factories and generators, effectively reducing the number of novel elements that required simultaneous processing in working memory.

The strong negative correlation between intrinsic and extraneous loads in the experimental group ( $r = -0.735$ ) revealed a compensatory relationship whereby reduced extraneous cognitive demands freed working memory capacity for intrinsic processing. This finding extends cognitive load theory by demonstrating that well-designed instructional media can create a “cognitive capacity dividend,” referring to freed mental resources that can be redirected toward schema construction rather than being consumed by irrelevant processing demands.

Regarding intrinsic load, the data indicated that the visual media product positively influenced students’ ability to comprehend complex and abstract scientific concepts by enhancing their meaning-making capacity. Visual media stimulated imagination, enabling students to construct meaning; consequently, they achieved better understanding of the concepts and higher learning achievement (Hanif, 2020; Lacković & Olteanu, 2020). This meaning-making process was further enhanced using metaphors and metonymy. Functioning as semantic tools, metaphors and metonymy operate by mapping the characteristics of a concept to be learned onto a concept that is already understood and stored in long-term memory, thereby reducing the abstractness of

the new concept. In other words, metaphors connect unfamiliar concepts to familiar ones based on shared characteristics, rendering abstract concepts more concrete and leading to deeper understanding (Brdar & Brdar-Szabó, 2020; Pettersson et al., 2020). Therefore, students demonstrated improved comprehension of complex concepts because the developed visual media facilitated meaning making and effectively reduced the abstractness of the concepts.

This compensatory mechanism aligns with recent innovations in instructional design for complex subjects. For instance, Sagoro et al. (2025) demonstrated that mathematics-based accounting learning materials, which simplified abstract rules by removing negative symbols from equations, similarly reduced students' cognitive load and improved learning performance in distance learning contexts. In both cases, whether through mathematical simplification or visual metaphors, the key instructional principle remains consistent: thoughtful manipulation of material presentation can optimize cognitive resource allocation.

### ***Comparison with previous research***

The findings of this study align with Purcell (2018) regarding the effectiveness of metaphors; however, the present study provides novel quantitative evidence of their specific impact on cognitive load components. While Pettersson et al. (2020) found that students used metaphors spontaneously, this controlled intervention demonstrated that systematically designed metaphor-based media can produce measurable learning advantages. However, these results contrast with Lancor (2015), who reported that student-generated metaphors sometimes contained misconceptions. In the present study, expert-validated metaphors avoided this limitation, suggesting that the source and quality of metaphors play a crucial role in their instructional effectiveness. The effect sizes obtained in this study ( $d = 0.75$  for intrinsic load,  $\eta^2 = 0.16$  for concept mastery) are comparable to, or exceed, those reported in meta-analyses of multimedia learning interventions (AlShaikh et al., 2024).

In relation to cognitive load management, the facilitated meaning-making process accounts for more effective information processing by increasing the amount of information that can be comprehended. This is because reduced abstraction allows students to allocate a greater portion of their cognitive capacity to information processing rather than to decoding abstract representations, thereby enabling more focused attention and effective processing. Given that complex concepts are inherently demanding due to the number of interrelated elements they comprise, a greater capacity to understand individual pieces of information enables the processing of a larger number of these elements, resulting in a more comprehensive understanding. Therefore, a relatively high intrinsic load in this context indicates effective cognitive load management. The experimental group's superior performance on the "Transfer to new contexts" indicator (87 compared to 73 in the control group) further demonstrates that students not only comprehended the taught metaphors but also developed flexible mental schemas that could be applied creatively to novel situations, a key indicator of deep and transferable learning.

Moreover, students in the experimental group responded positively to the lesson and frequently described it as interesting and engaging. This aligns with research indicating that the use of metaphors and metonymies, which draw on familiar words, concepts, and everyday experiences, positively influences students' attitudes toward learning abstract or challenging concepts (Kupferman, 2018). Visual media has similarly been shown to create a more engaging and interactive learning environment, fostering students' creativity, motivation, and interest in science (Ommering et al., 2020). Consequently, the visual media developed in this study, based on metaphors and metonymies, not only supported deeper understanding but also increased learning engagement, leading to greater interest and more positive attitudes toward science learning. Qualitative feedback from students reinforced this finding, with many expressing enthusiasms to learn more about cells and other biological topics.

It is important to note that the observed increase in intrinsic load was a consequence of reduced extraneous load, a necessary adaptation given the limited capacity of working memory. Extraneous load, defined as the cognitive burden imposed by external factors such as instructional design and teaching strategies, was mitigated in this study using visual media based on metaphors and metonymies. By modifying information delivery, these media decreased extraneous load,

thereby freeing cognitive resources for intrinsic processing of complex information. This reduction in extraneous load is evidenced by the low mental effort required of students to comprehend the presented concepts. For example, 47.7% of students in the experimental group rated the content as “easy,” compared to only 20.3% of students in the control group. Consistent with the findings of this study, the lower mental effort in the experimental group can be attributed to the use of metaphors and metonymies that facilitated students in relating abstract concepts to more familiar ideas, easing the construction of cognitive schemas through stronger connections between newly learned information and information stored in long-term memory. As a result, students demonstrated improved comprehension and enhanced long-term retention of complex concepts. This result agrees with prior research indicating that the simultaneous presentation of information in both verbal and visual formats can reduce extraneous load and improve learning outcomes (Albus et al., 2021; Castro-Alonso et al., 2021). Similarly, research on the visualization of reading materials suggests that strategies that transform verbal information into visual representations can reduce extraneous load and increase understanding and learning outcomes (Skulmowski & Xu, 2022). The expert feedback highlighting improved synchronization and visual hierarchy further supports the notion that thoughtful instructional design can substantially reduce unnecessary cognitive burden.

This finding is consistent with research on microlearning strategies, which emphasize breaking content into small, focused segments to prevent cognitive overload. Susilana et al. (2022) found that microlearning effectively mediated students' cognitive load in online learning by presenting information in manageable units, resulting in low intrinsic and extraneous loads. Their study demonstrated that when content is segmented appropriately, whether through microlearning modules or metaphor-based visual media, students can process complex information more efficiently, as reflected in lower mental effort ratings and improved learning outcomes.

While effective strategies for facilitating learning and meaning making are valuable, they do not guarantee successful learning. Learning, defined as the storage of information in long-term memory for later retrieval (Paas & van Merriënboer, 2020), can only be considered successful when students retain learned concepts. Therefore, this study also analyzed students' concept mastery through the assessment of germane load in order to examine the process of information transfer from working memory to long-term memory. The results of the germane load measurement indicated that students in the experimental group achieved higher concept mastery compared to their control group counterparts. This improvement is attributed to the use of metaphors and metonymies, which effectively visualize information during processing and present key concepts in a familiar and accessible manner (Abawi, 2013). Furthermore, the integration of audio-visual media with metaphors and metonymies, supplemented by visual aids such as images and graphs, facilitated more efficient construction of cognitive schemas and the transfer of information to long-term memory, ultimately leading to deeper comprehension and enhanced retention.

Additionally, the correlation test data showed a positive correlation between intrinsic load and germane load, suggesting a proportional relationship between information processing capability and the level of concept mastery. Conversely, the negative correlation between extraneous and germane load implies that minimizing mental effort enhances concept mastery. This pattern was particularly pronounced in the experimental group, where the intrinsic–germane correlation ( $r^2 = 0.785$ ) was substantially stronger than the extraneous–germane correlation ( $r^2 = 0.578$ ), indicating that learning success was driven primarily by effective information processing rather than by managing instructional complications. In contrast, the control group showed a reversed pattern, with extraneous load playing a more dominant role ( $r^2 = 0.676$ ), suggesting that students expended considerable cognitive resources navigating instructional challenges rather than engaging in productive learning. This analysis demonstrates how visual metaphors and metonymies facilitate cognitive load management during the learning of complex scientific concepts. By modulating both intrinsic and extraneous load through contextual delivery and by supporting abstraction and meaning making, the developed visual media enabled greater information processing ability with less mental effort, resulting in effective learning and retention.

### ***Practical and theoretical implications***

For educational practice, the findings of this study offer concrete guidance for science educators and curriculum developers. When introducing abstract concepts, teachers should identify appropriate *source domains* that share structural similarities with the *target domains* to support conceptual mapping and contextualization. Teacher professional development should emphasize metacognitive awareness of how instructional design decisions shape students' cognitive load. For educational technology design, the results inform principles for developing cognitive load-optimized media. Specifically, dynamic visualization with carefully timed narration, combined with metaphorical representation, may create a "triple support" system that strengthens comprehension by integrating verbal explanation, visual depiction, and contextual metaphor. Theoretically, the findings extend cognitive load theory by demonstrating that metaphorical representation can modulate element interactivity, which has often been treated as a relatively fixed characteristic of learning materials.

### ***Limitations and future directions***

This study addressed three research questions regarding the effectiveness of visual metaphors and metonymies in managing cognitive load when learning cell biology concepts. Overall, visual metaphors and metonymies were effective in supporting cognitive load management, with substantial practical significance as indicated by large or moderate-to-large effect sizes ( $d = 0.75$  for intrinsic load; Cramér's  $V = 0.34$  for extraneous load). Across the measured components, the experimental group consistently outperformed the control group. The metaphor-based visual media was associated with higher intrinsic load, lower extraneous load, and improved germane outcomes, as reflected in higher concept mastery. Correlation analyses further suggested that the intervention altered the pattern of relationships among load components, with intrinsic processing becoming a stronger driver of learning outcomes. Students exposed to the metaphor-based visual media demonstrated significantly better concept mastery (partial  $\eta^2 = 0.16$ ) and showed particular strengths in higher-order cognitive tasks involving organization and synthesis. Notably, the benefits appeared more pronounced as cognitive complexity increased, indicating potential value for challenging abstract concepts.

These findings suggest that visual media employing metaphors and metonymies can shape how students process abstract scientific information, making complex concepts more accessible while maintaining conceptual accuracy. By connecting abstract scientific ideas to familiar contexts, metaphors and metonymies may reduce extraneous cognitive load and support deeper understanding. Thus, metaphor- and metonymy-based visual media represents a promising approach for teaching complex and abstract science concepts by strengthening mental representations and mitigating cognitive load barriers.

Future research should extend the methodological scope to strengthen the evidence base for metaphor-based instruction. Longitudinal studies incorporating delayed post-tests at 3, 6, and 12 months are needed to examine retention trajectories and the durability of learning gains. Cross-domain comparative studies in physics, chemistry, and earth science could help distinguish universal design principles from domain-specific requirements in metaphor selection. In addition, investigating individual differences such as spatial ability, verbal ability, prior knowledge, and cognitive style could inform adaptive and personalized approaches that optimize metaphor-based learning across diverse learner populations.

From a practical perspective, systematic frameworks for metaphor selection and validation should be developed and empirically tested across varied educational contexts, with explicit attention to conceptual accuracy, cultural relevance, and misconception risks. Finally, integration studies examining potential synergies between metaphor-based instruction and other evidence-based techniques (e.g., worked examples, spaced practice, and interleaving) would inform comprehensive instructional design models that more holistically address cognitive load challenges in science education.

## CONCLUSION

This study concludes that visual media employing metaphors and metonymies is highly effective in managing students' cognitive load when learning complex scientific concepts like cell biology. The intervention significantly improved cognitive load management across all components, as evidenced by large effect sizes. Students using the metaphor-based media demonstrated better information processing (higher intrinsic load), required less mental effort (lower extraneous load), and achieved superior concept mastery and retention (higher germane load), particularly in higher-order thinking tasks. The findings suggest that this approach transforms abstract information processing by connecting new concepts to familiar contexts, thereby reducing cognitive barriers and promoting deeper, more durable learning.

Future research should employ longitudinal designs to assess long-term retention and conduct cross-disciplinary studies to validate these findings. Investigating the influence of individual learner differences is also crucial for developing more personalized and adaptive instructional models. Practically, the development of systematic frameworks for metaphor selection, ensuring conceptual and cultural appropriateness, is recommended to optimize the implementation of this approach in diverse science education settings.

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