The impact of visual imagery vividness in learning dynamic biological processes using visualizations

Master Thesis Science Education and Communication

R. R. van Swieten (5641454)
12-08-2024
r.r.vanswieten@students.uu.nl
Freudenthal Institute
Rogier Bos
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Content

Abstract

This study focused on the educational impact of displaying kinematic changes in visualizations when learning dynamic biological processes, exploring the influence of vividness of visual imagery and visual cognitive style on the learning effect of dynamic and static visualizations. This study was conducted through an experiment conducted at Dutch high school classes (n=32, M_{age} = 15.63, SD_{age} = .61, 56.3% male), using dynamic and static visualizations of the electron transport chain. The participants were divided over the two conditions using stratified randomization based on the biology grade, done by the biology teacher to ensure a double-blind design. The experiment included two questionnaires (VVIQ and IDQ-IHS), the intervention video regarding the ETC, and a post-test designed to assess students' comprehension of the spatial and functional aspects of the electron transport chain. Results indicate no significant difference in learning outcomes between the dynamic and static visualization groups. Further, no significant aptitude-treatment-interactions were found between vividness, visual cognitive style, and the type of visualization. In sum, this study substantiates the importance of a well-designed visualization that is aligned with students' prior knowledge, and suggests that future research explore alternative cognitive strategies and repeated exposures to dynamic visualizations.

Key words: Dynamic visualization, Kinematic Change, Biology education, Cognitive abilities, Vividness of visual imagery (VVIQ), Cognitive style (IDQ-IHS)

Personal note:

This took me 1.5 years. I want to thank my parents and sister, my supervisor Rogier Bos, Madelief Medema, and my friends, for helping me whenever I needed help. I also want to thank the high school teachers who helped me with enthusiasm to conduct the experiments. I enjoyed working on this thesis, but I'm also happy I'm done.

Introduction

In an era of rapidly expanding knowledge and technological advancement, educators face the pressing challenge of conveying increasingly complex information effectively. Traditional educational materials, such as textbooks, are being supplemented and often supplanted by digital tools designed to enhance learning outcomes (Çeken & Taşkın, 2022; Lockee, 2021; Nasir et al., 2021). The COVID-19 pandemic catalyzed a shift toward innovative educational strategies, forcing educators to adopt and refine new methods, including the use of video-based instruction (Lockee, 2021). However, this shift was already shown over the last decade within informal education, with the prevalence of educational videos on multimedia platforms like Netflix and YouTube rapidly increasing, offering a tremendous amount of content that engages millions of learners. However, the creation of scientifically based videos for formal education has not kept pace with this trend, despite the urgent need for such resources to ensure that educational content is both effective and aligned with evidence-based teaching practices. As these informal platforms continue to expand, there is a growing necessity to integrate scientifically validated approaches into video production for formal educational settings.

A critical area of interest in this context is the role of visualizations in learning, and the design of instructional methods. *Static visualizations*, such as diagrams and images, have long been a staple in educational materials, but *dynamic visualizations*, which depict processes and systems in motion, are increasingly recognized for their potential to enhance comprehension of complex phenomena (Ploetzner et al., 2020). Dynamic visualizations can illustrate changes over time, providing learners with a more integrated understanding of how mechanisms evolve and interact (Bétrancourt & Benetos, 2018). This is particularly relevant in educational contexts where the dynamic process is difficult to observe directly, and where understanding changes over time is desired, such as disciplines like biology (Höffler, 2010). Dynamic visualizations have great potential, especially in biology education, due to the inherent dynamic nature of biological processes. *Biological processes* often involve multiple interacting components that change over time and space. Often molecular in nature, these movements and interactions are challenging to convey through static images, making dynamic visualizations particularly suitable for visualizing biological processes (Berney & Bétrancourt, 2016; Bétrancourt & Benetos, 2018). By allowing students to see these dynamic processes in action, it was hypothesized that dynamic visualization could enhance the understanding and retention of complex biological concepts (Höffler, 2010). However, despite the theoretical advantages of dynamic visualizations, empirical research has produced mixed results regarding their effectiveness (Berney & Bétrancourt, 2016; Bétrancourt & Benetos, 2018; Höffler, 2010). A meta-analysis conducted by Berney and Betrancourt (2016) found that 59.3% of pair-wise comparisons showed no significant difference between static and dynamic visualizations. Notably, biology was the least significantly effective science domain to use dynamic visualization for (Berney & Bétrancourt, 2016; Castro-Alonso et al., 2019). This discrepancy between the expected benefits and the actual empirical findings raises questions about the efficacy of visual materials and the underlying mechanisms that influence learning with dynamic visualizations in biology education.

One aspect that is increasingly taken into account in the advancement of educational materials and instructional methods, is the application of psychological principles of human learning (Çeken & Taşkın, 2022;

Lockee, 2021; Nasir et al., 2021). These principles take individual, psychological constructs into account that are influential on the learning process (Ormrod et al., 2023). While these principles have been recognized in traditional education, such as the influence of dyslexia and dyscalculia, the effect of these principles in modernized education materials is still ambiguous (Bucci, 2021; Duranovic et al., 2015; Ritchie et al., 2015). Specifically, research on the effect of individual differences in learning and problem-solving with video formats is, as far as found, inconsistent (Bétrancourt & Benetos, 2018; Höffler, 2010; Kühl et al., 2020; Ploetzner et al., 2020). While visualization constructs such as cognitive style, mental imagery, mental visual manipulation, and design principles have been broadly studied, the knowledge about their role in visual educational materials is limited and ambiguous (Keogh & Pearson, 2024; Kühl et al., 2022). By carefully considering these principles in educational research, the design of teaching materials and methods can be improved, potentially leading to increased engagement and higher learning outcomes for students.

The rapid development and changes in educational settings call for exploratory research and empirical evidence, to better understand how we can use and advance educational strategies to best facilitate learning. This study aims to fill a crucial gap in understanding by exploring the differences within visualizations, and including individual differences in psychological constructs that may affect the processing of visual information. Specifically, we focus on the dynamic processes in biology education, the influence of the vividness of visual imagery, and differences in visual information processing due to cognitive style. By investigating these factors, this research seeks to provide valuable insights that can guide the development of more effective educational videos, ultimately improving the quality of science education in the digital era.

Theoretical background

Kinematic change

When visualizing biological processes, static and dynamic visualizations vary in their effectiveness in conveying the targeted information. Ploetzner et al. (2020) reanalyzed meta-analyses comparing dynamic and static visualizations, identifying kinematic changes as an important moderating variable. *Kinematic changes* refer to movements within visualizations that correspond to changes in spatial and temporal dimensions, or changes in time and space. They display aspects of motion that cause changes in spatial organization (Ploetzner et al. 2020). Dynamic visualizations resulted in significantly higher learning outcomes than static representations if the dynamic features of the displayed changes had to be learned (Ploetzner et al., 2020). Their results suggest that the strength of dynamic visualizations lies in their ability to facilitate the creation of a kinematic mental model. These models represent movements and interactions within biological systems and help students understand complex automatic processes. Static representations, however, may not effectively convey these dynamic aspects, potentially limiting the formation of accurate mental models.

An essential advantage of visualizations is their ability to help students construct a mental model (Windhager & Mayr, 2023). *Mental models* are internal representations individuals create and use to understand and infer complex mechanistic processes (Hegarty et al., 2003; Liu & Stasko, 2010). Visualizations help students construct mental models, as they convey information about spatial organization that text alone cannot easily provide (Höffler, 2010). Ploetzner et al. (2020) differentiate between conceptual and kinematic mental models. A *kinematic mental model* is an analog representation of displayed changes, unfolding chronologically and involving sequential events analogous to the visual changes (Hegarty et al., 2003). In contrast, a *conceptual mental model* involves symbolic representations of relations, concepts, abstractions, laws, and principles that explain and describe the displayed changes (Anderson et al., 2001).

Dynamic visualizations offer several advantages over static images by depicting subtle, transient changes that occur within biological systems, such as shifts in direction, velocity, acceleration, orientation, and appearance (Hegarty & Steinhoff, 1997; Hegarty et al., 2003; Hegarty & Sims, 1994). These changes, which are difficult to infer from static images, are directly observable in dynamic visualizations, providing a clearer and more intuitive understanding of complex processes (Ploetzner et al., 2020). Displaying kinematic changes helps students construct detailed and accurate kinematic mental models, which are essential for mastering the material. However, dynamic visualizations also present challenges; they contain more visual information than static representations, which can increase the cognitive load on students. *Cognitive load* refers to the amount of information that needs to be processed in working memory (Paivio, 1983). Research by Lowe et al. (2003, 2011) suggests that if the visual information is too complex or abundant, it can overwhelm students, making it difficult for them to integrate the information into their long-term memory. Multimedia design principles grounded in fundamental theoretical frameworks such as the cognitive load theory, constructivism learning theory, and the dual-coding theory, can lower the cognitive load associated with dynamic visualization (Paivio, 1983; Piaget, 1964; Sweller, 1988). These principles aim to reduce cognitive overload and make dynamic visualizations more effective as learning tools.

The effectiveness of dynamic visualizations, compared to static ones, depends largely on the cognitive load they impose and the learner's ability to manage that load. Individual differences in cognitive abilities, particularly visuospatial skills, play a significant role in how well students learn from visualizations (Höffler, 2010; Kühl et al., 2022). *Visuospatial abilities* are a set of cognitive skills that enable individuals to perceive, comprehend, and manipulate visual and spatial information in their minds (Höffler, 2010; Kühl et al., 2022; Carrol, 1993). These skills are particularly important for processing dynamic visualizations, which often require students to mentally track and interpret moving objects, and changing visual representations. These abilities may help students manage the cognitive load associated with dynamic visualizations, while also helping with interpreting static images where students must infer changes. Despite the ambiguity in the literature, it is clear that visuospatial abilities are indispensable skills in biology education that provide the ability to mentally rotate, twist, or invert objects, and manipulate the spatial organization of a dynamic system (Hegarty & Waller, 2005). Research investigating visuospatial abilities and types of visualization remains unclear, indicating additional factors may influence this interaction (Kühl et al., 2022; Carrol, 1993; Hoffler, 2010).

Vividness of visual imagery

Besides differences in visualization types, mental factors such as the vividness of visual imagery may also influence the effectiveness of learning through visualizations. The *vividness* of visual imagery refers to the clarity, brightness, and detail with which individuals can generate mental images (Pearson et al., 2015; Pearson & Keogh, 2019). This trait varies significantly among individuals and can impact their ability to process and learn from visualizations. In the context of dynamic visualizations, vivid visual imagery can enhance the construction of mental models by making the visualized processes more perceptible and easier to recall (Keogh et al., 2021). Exploring this concept helps to understand how individual differences in visual imagery vividness can moderate the effectiveness of visualization type.

Bètrancourt et al. (2016) mentioned that visualizing the spatial organization of biological processes is essential for mastering biological concepts. Using mental models in problem-solving scenarios requires creating a visual representation in the mind’s eye. The clarity of these visual representations is influenced by the vividness of visual imagery. According to Liu and Stasko (2010), mental simulations form the foundation of model-based reasoning. When individuals simulate a dynamic process, they must create visual representations of kinematic mental models in their minds. Mental imagery, in general, is the act of generating a conscious sensory experience in the mind without external input (Pearson, 2019). Although mental imagery can involve all senses, most research has focused on *visual imagery*, which involves forming images of objects, people, or scenarios in the mind. Recent studies have linked visual imagery to various cognitive processes, including memory, spatial navigation, reading comprehension, creativity, emotions, and decision-making (Aydin, 2018; Keogh & Pearson, 2011, 2014; Pearson & Keogh, 2019; Wicken et al., 2021). The ability to use visual imagery is a fundamental aspect of learning and problem-solving (Hegarty & Steinhoff, 1997; Hegarty et al., 2003).

However, research into specific aspects of visual imagery, particularly vividness, is limited. This research is needed to fully understand its impact on learning and problem-solving, and to be able to create effective visual learning materials that suit the targeted learning outcomes (Pearson et al., 2015). While the specific role remains unclear, visuospatial abilities essentially refer to cognitive processes that gather and combine stored information to form, comprehend, and transform visual representations in the mind. The vividness refers specifically to the clarity and brightness of these visual representations (Pearson & Keogh, 2019). Zeman and colleagues (2015) found that people's ability to create mental images varies widely, with some individuals experiencing very clear and lifelike images (Hyperphantasia) and others being unable to form mental images at all (Aphantasia) (Keogh & Lau, 2024). Vividness appears to be an inherent trait that cannot be enhanced through training, relying solely on the excitability of specific neurons in the visual cortex (Keogh et al., 2020; Rademaker & Pearson, 2012). The variation in vividness might influence how students perceive the spatial organization of a kinematic mental model.

Although research on vividness in education is still limited, some studies suggest that vivid visual imagery is associated with greater visual working memory capacity (Keogh & Pearson, 2014). Higher vividness might allow students to integrate larger chunks of visual information into memory, which could improve learning outcomes (Koopman & Newtson, 1981). A clear mental image of a kinematic model could also aid students in solving problems related to spatial organization. For instance, Jankowska and Karwowski (2020) found that individuals with vivid imagery scored higher on tasks requiring creative visual imagery, indicating that vividness can be beneficial for tasks that involve creativity and visualization. However, the relationship between vividness and learning is not straightforward. For example, Thorudottir et al. (2024) found no significant link between vividness and the accuracy of visual long-term memory. Similarly, Bates and Farran (2021) found no significant correlation between mental imagery tasks and visual working memory, suggesting that the strategies individuals use during these tasks might explain the lack of direct correlations.

The strength of dynamic visualizations lies in their ability to depict kinematic changes and facilitate the creation of kinematic mental models. It is plausible that vividness plays a role in how effectively students can process and use these visualizations. Understanding how vividness affects learning with different types of visualizations could help clarify some mixed results found in the literature (Berney & Bétrancourt, 2016; Bétrancourt & Benetos, 2018; Höffler, 2010; Kühl et al., 2022; Ploetzner & Lowe, 2012). Further exploration of this aptitude-treatment interaction is needed to determine how best to support students with varying levels of vividness in their visual imagery.

Cognitive style

Individual differences extend not only to the vividness of visual imagery, but also to the cognitive processes associated with information processing. *Cognitive style* relates to individuals' information-processing behaviors and reflects the dominant modes of perceiving, remembering, thinking, and problem-solving (Thi et al., 2021). Students only benefit from visualizations if the visual information is processed adequately. Evidence suggests that adjusting learning settings to accommodate learning styles greatly contributes to academic achievement (Li et al., 2009; Thi et al., 2021). Understanding the influence of cognitive style on learning from visualizations is important, as individuals may differ in how they process information (Riding & Rayner, 1998). This study specifically focuses on visualizers and the extent to which visualization strategies are employed.

The existence of cognitive styles as distinct routes for information processing is openly debated. Massa & Mayer (2006) investigated the educational relevance of cognitive styles, particularly focusing on verbal and visual learning, but found no significant advantage for aligning teaching methods to cognitive styles. Contrastingly, Koć-Januchta et al. (2017) found distinct patterns in the gaze behavior of visualizers and verbalizers while learning from pictures and texts. Visualizers spent significantly more time looking at visual information, whereas verbalizers spent more time looking at the text and tended to look at irrelevant visual information sooner than visualizers. Verbalizers rely on phonological and verbal working memory for problem-solving, leading to lower learning outcomes when learning with visual educational material than visualizers. These findings align with Höffler et al. (2010), indicating that individuals who naturally employ visual strategies benefit more from visual aids than those who do not.

Research on visual cognitive styles indicates that individuals use visual imagery in two distinct ways: object and spatial visualization (Blazhenkova & Kozhevnikov, 2009; Höffler et al., 2017; Kozhevnikov et al., 2005). Object visualizers primarily form holistic mental representations of objects or events, encoding images as a single perceptual unit. In contrast, spatial visualizers process images analytically as multiple distinct units and excel in tasks involving spatial relationships and mental transformations (Höffler et al., 2017). Spatial visualization is particularly relevant for tasks that require spatial reasoning and mental manipulation, as it allows individuals to create and transform visual images to solve problems or understand spatial relationships (Pearson, 2022; Blazhenkova & Kozhevnikov, 2009).

In addition to visual imagery, individuals use a variety of strategies for spatial reasoning and manipulation. Even those without visual imagery, such as individuals with aphantasia, can successfully perform tasks involving visual working memory and retrieve episodic memories (Aydin, 2018; Dawes et al., 2022; Keogh & Pearson, 2024). Kay and colleagues (2024) found that people with aphantasia, when asked to complete a mental rotation task—a task indicative of spatial visualization—took longer but were more accurate. This finding suggests that visual imagery is just one of several strategies used in spatial tasks. Individuals with aphantasia may rely on non-visual cognitive processes, such as abstract reasoning or verbal strategies, to achieve similar levels of performance. This underscores the importance of considering whether visual imagery is employed in tasks and learning contexts (Höffler et al., 2010; Kay et al., 2024; Walsh et al., 2021).

Cognitive fit: Kinematic change, vividness, and cognitive style

The *cognitive fit theory* proposed by Li et al. (2009) posits that students' performance, in engagement, recall, and comprehension depends on how well the presentation of information aligns with their cognitive characteristics and the nature of the task at hand. This chapter explores the combined effects of kinematic change, visual imagery vividness, and cognitive style on learning outcomes.

Visualizations are known to aid in the creation of mental models, which are important for understanding complex information (Windhager & Mayr, 2023; Ploetzner et al., 2020). These mental models represent the dynamic and spatial aspects of the visual information. The vividness of visual imagery refers to the strength and clarity of these mental representations, while cognitive style encompasses how individuals process information and employ cognitive strategies during learning and problem-solving tasks. Students with a visual cognitive style are generally expected to benefit more from visualizations because their preferred way of processing information aligns with visual modes of learning. However, the effectiveness of these visual strategies also depends on the vividness of their visual imagery. For a student to effectively perceive and mentally represent kinematic changes, they need to have a sufficient level of vividness. Visualizations are most effective for those with both a strong visual cognitive style and high vividness. Conversely, if a student has high vividness but does not naturally use visual cognitive strategies, vividness alone may not lead to improved learning outcomes. On the other hand, students with a visual cognitive style but low vividness might struggle to benefit from visualizations because they cannot form clear mental images of the kinematic models.

The interplay between design principles and varying cognitive aptitudes highlights the complexity of optimizing visualizations for learning. While visuospatial abilities provide the capacity to process and manipulate visual information, cognitive style determines the use of this capacity, and vividness influences the effectiveness of this use. In educational science, the impact of these cognitive characteristics on the learning effect of different educational materials is referred to as aptitude-treatment interactions (ATIs) (Snow, 1989). The vividness of visual imagery could play a moderating role in the effectiveness of both dynamic and static visualizations, similar to how visuospatial abilities influence learning, as suggested by Kühl et al. (2022). They propose two contrasting hypotheses within this framework.

The *ability-as-enhancer hypothesis* posits that a certain level of vividness is necessary to mitigate the additional cognitive load associated with dynamic visualizations. This implies that students with low vividness may not fully benefit from dynamic visualizations. However, when vividness is sufficient relative to the cognitive demands of the task, the advantages of dynamic visualizations become more apparent. Conversely, the *ability-as-compensator hypothesis* states that a certain level of vividness is necessary to infer the kinematic changes in static pictures. Individuals with low vividness cannot infer changes in static representations and therefore benefit from dynamic visualization, serving as a template for mental model construction. Individuals with high vividness can infer the changes in static representations, thus ensuring successful learning outcomes even with static representations. According to this hypothesis, the most significant differences in learning outcomes between different visual designs are expected to occur among students with medium levels of vividness, consistent with the unifying conceptualization (Kühl et al., 2022).

In summary, the cognitive fit between a student's cognitive style, their level of vividness, and the design of visualizations plays a significant role in determining the effectiveness of these educational tools. Understanding these interactions can help optimize learning materials to better meet the diverse needs of students.

Present study

The theoretical findings raise the question of to what extent the vividness of visual imagery and visual cognitive style influence the learning effect of dynamic visualizations of dynamic biological processes displaying kinematic change. Therefore, to broaden our understanding of underlying cognitive strategies and aptitudes that dictate the learning efficacy of dynamic visualization in biology education, the present study investigates the following three hypotheses:

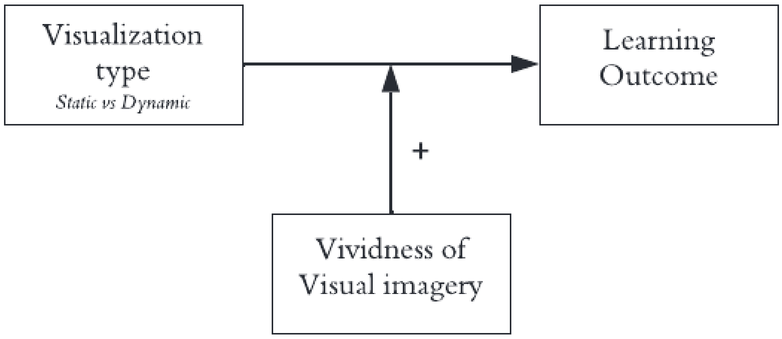
Hypothesis 1: Dynamic visualization focused on kinematic change is more beneficial for learning dynamic biological processes than static representations that do not display kinematic changes.

Empirical evidence regarding the effectiveness of dynamic visualization over static representation in biology education remains inconclusive (Berney & Bétrancourt, 2016; Bétrancourt & Benetos, 2018; Höffler, 2010; McElhaney et al., 2015; Ploetzner et al., 2020). Therefore, this study aims to clarify to what extent dynamic visualization focused on kinematic changes influences the learning outcome of dynamic biological processes. Dealing with questions related to dynamic biological processes requires using constructed mental models. Dynamic visualization is expected to result in increased learning outcomes compared to static representations if displaying kinematic changes facilitates or enables the construction of kinematic mental models.

Hypothesis 2: There is an aptitude-treatment interaction between the vividness of visual imagery and learning dynamic biological processes with static representations or dynamic visualizations focused on kinematic change.

The vividness of visual imagery influences the use and construction of mental models. We aim to clarify the influence of one's vividness of visual imagery on the efficacy of learning dynamic biological processes with either static representations or dynamic visualization focused on kinematic change. This aptitude-treatment interaction proposes two contrasting hypotheses: the ability-as-enhancer hypothesis, where high vividness enhances learning with dynamic visualizations, and the ability-as-compensator hypothesis, where high vividness compensates for suboptimal static representations (Kühl et al., 2022). We expect that dynamic visualizations will be more effective for individuals with high vividness if a larger visual-working capacity enhances the recollection and manipulation of visual information (Figure 1) (Keogh & Pearson, 2014). This aligns with the ability-as-enhancer hypothesis, where learners with adequate vividness benefit most from optimized visualization.

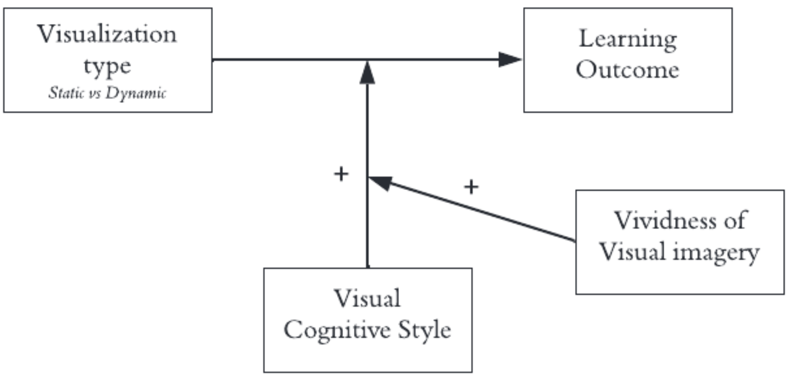
Figure 1. Hypothesis model for the moderating effect of vividness on the learning effect of visualization type



Hypothesis 3: The moderating effect of visual cognitive style on the relationship between learning outcome and type of visualization is moderated by the vividness of visual imagery.

High visual imagery vividness does not necessarily equate to using visual imagery in educational settings during problem-solving tasks. Therefore, we aim to gauge the influence of the degree of using visualization in educational settings on the learning effect of static representations or dynamic visualization. We expect that the vividness of visual imagery positively moderates the moderating effect of visual cognitive style on the learning effect when learning biological processes using either static or dynamic visualizations. If one uses vivid visual imagery for reasoning and problem-solving in daily life, then he or she might heavily benefit from dynamic visualizations (Figure 2). Individuals with high vividness and a visual cognitive style may recall and utilize kinematic changes in dynamic visualizations more effectively (Keogh et al., 2020; Keogh & Pearson, 2014).

Figure 2. Hypothesis model for moderating moderation effect of vividness and visual cognitive style on learning effect of visualization type



Methods

Study design and procedure

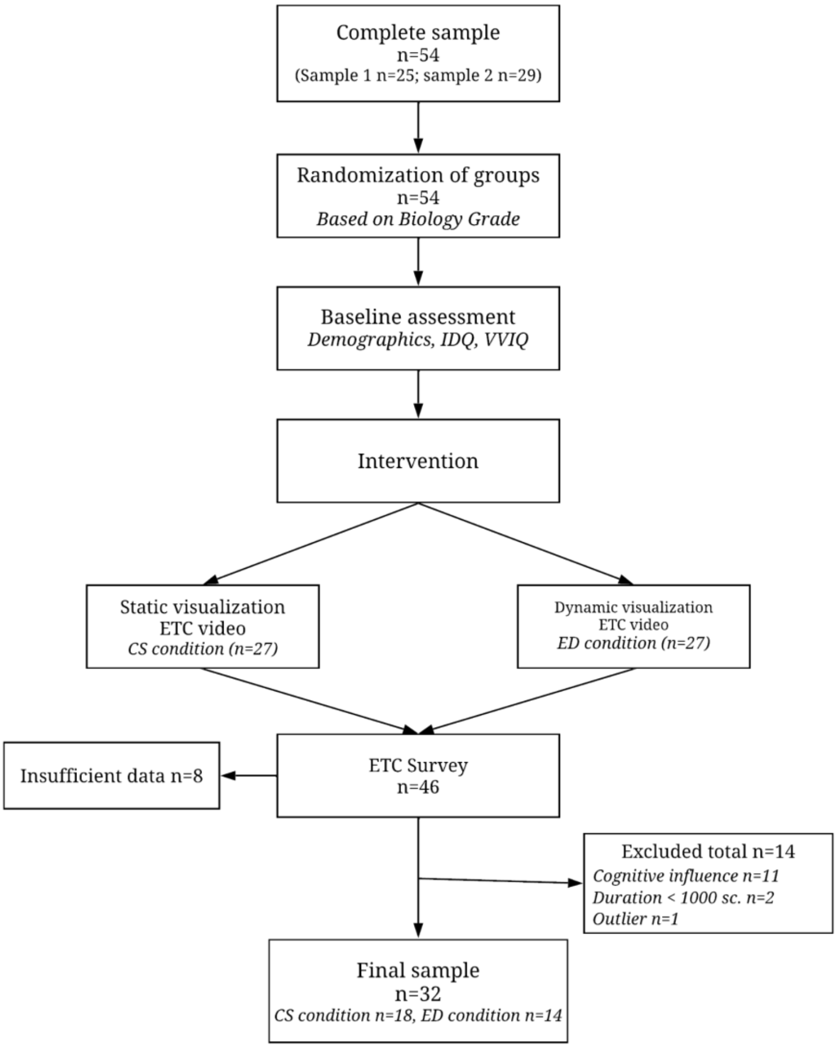
We conducted a quantitative experiment to compare the effectiveness of dynamic visualizations and static representations in teaching dynamic biological processes. Additionally, we investigated the potential moderating effects of the vividness of visual imagery and visual cognitive style on the learning effect of static and dynamic visualization. This study used a post-test-only intervention design (Figure 3). This approach was chosen to measure the learning effect of new biological concepts rather than the activation of pre-existing knowledge. Therefore, only classes which had not been formally educated yet on the electron transfer chain were included. Data collection occurred during biology class in a classroom setting. The classroom environment was arranged to facilitate individual engagement with the visual materials, with each student having access to a personal computer or tablet and audio device (headphones or earpieces). Informed consent was obtained from all participants before their involvement in the study. The form included information about the study's purpose, expected duration, descriptions of the procedures and tasks, voluntary participation, and assurances of confidentiality, anonymity, and data protection (Appendix A).

Data was collected using the online survey platform Qualtrics^{TM}, which was distributed through a link sent out by the biology teacher. The email consisted of a short instruction and the distribution of the participants across the two conditions. To ensure comparability, participants were equally assigned to the dynamic visualization or static representation groups, using stratified randomization based on average biology grades. This ensured equal distribution of academic performance between groups. Utilizing a double-blind design, the participant distribution was performed by the biology teacher, ensuring that the participants and the experimenter were unaware of group assignments during the experiment.

The experiment was divided into three phases: first, students provided demographic information, including age, gender, and average biology grade, along with exclusion criteria questions (Appendix B). These questions were followed by two questionnaires: the Vividness of Visual Imagery Questionnaire (VVIQ) and the Individual Differences Questionnaire on Imagery Habitual Strategies (IDQ-IHS). Secondly, students were invited to watch an instructional video explaining the electron transfer chain (ETC), a core VWO biology curriculum requirement. The participants were automatically directed to the intervention video belonging to the assigned group. In the final section, learning outcomes were assessed using a post-test, consisting of 14 open questions regarding the ETC. This design enables the comparison of learning outcomes between dynamic visualizations and static representations. Additionally, this design allows the assessment of how the vividness of visual imagery and the habitual use of visual imagery moderate the effects of visualization type in educational settings. The experiment took approximately 40 minutes, including all phases.

To ensure this study's focus on the specific cognitive influences of vividness and cognitive visual style, participants with diagnosed conditions such as ADHD/ADD, autism, dyslexia, and dyscalculia were excluded from the research. The exclusion of these specific conditions is based on empirical evidence, showing that these conditions significantly impact cognitive processes involved in learning (Lewis. 2008). Additionally, participants with uncorrected visual impairments, such as myopia, hyperopia, and colorblindness, were excluded. However, due to the classroom setting of the experiment, it was decided to not inform the students of their exclusion, but to remove the data later on. This approach reduced the possibility of any disturbances by excluded students and takes the sensitivity of these exclusions into account (Flory & Emanuel, 2004). By controlling for these variables, the study aims to provide clearer insights into the effects of visual imagery and cognitive visual style on learning outcomes while controlling for possible confounders. Furthermore, participants who had multiple missing data points and finished the experiment below the minimum expected time duration (calculated by the average duration time and the expected duration calculated by Qualtrics™), were excluded. This exclusion was based on the possibility of participants not fully engaging with the content, skipping questions, or providing random answers without thoughtful consideration (Nulty, 2008). By removing these participants, we aimed to reduce the likelihood of including data that may not accurately reflect genuine responses or the cognitive processes being studied.

Figure 3. Study design



Participants

Data for this study was collected from two high schools in Utrecht, the Netherlands. Only 4th-year biology students from these schools were included, resulting in 54 participants. Eight participants were excluded due to incomplete data, two for insufficient duration time, 11 due to cognitive influences, and one outlier was removed. The final sample consisted of 32 participants (56.3% male, 43.8% female) with a mean age of 15.63 (SD = .609, range = 14-17). The first school provided 19 participants (59.4%), while the second provided 13 (40.6%). The final sample had a mean biology grade of 6.89 (n=31, SD = 1.21), which ranged from 3.9 to 9.3, based on the 10-point scale education grading system. These participants were assigned to either the experimental-dynamic (ED) condition (n=14) or the control-static (CS) condition (n=18).

Instruments and Measures

Vividness of Visual Imagery Questionnaire (VVIQ)

We used the Vividness of Visual Imagery Questionnaire (VVIQ), a self-report instrument designed to measure the vividness of an individual's visual imagery (Marks, 1973). To administer the questionnaire to Dutch adolescents, we translated the items into Dutch, taking the vocabulary of adolescents into account. The VVIQ consists of 16 items that invite participants to imagine four specific scenarios and rate the clarity and strength (vividness) of their imagery on a 5-point Likert scale, from 'Perfectly clear and as vivid as normal vision' (1), to 'No image at all, you only 'know' that you are thinking of an object' (5) (Appendix C[1]). Scores were calculated by summing the responses from all items, with lower scores indicating more vivid imagery. To test the hypotheses, the scores were reversed so that higher scores indicated higher levels of vividness. Previous studies have demonstrated excellent reliability for the VVIQ with a Cronbach's alpha of .90 (Jankowska & Karwowski, 2022). The VVIQ also showed good reliability in our study (α = .82).

Individual Differences Questionnaire on Imagery and Habitual Strategies (IDQ-IHS)

In addition to the VVIQ, we used a modified, shortened version of the Individual Differences Questionnaire on Imagery and Habitual Strategies (IDQ-IHS), which measures the habitual use of visual imagery and verbal strategies (Paivio & Harshman, 1983). This questionnaire was translated into Dutch, with suitable vocabulary for Dutch adolescents (Appendix C[2]). This adapted version consists of 15 items related to the use of visual imagery, rated on a 5-point Likert scale from 'strongly disagree' (1) to 'strongly agree' (5). In this adapted version, two additional problem-solving items from the original questionnaire were added to enhance the focus on visual cognitive processes in learning environments (Krellenstein, 1994). To calculate the mean scores of the IDQ-IHS, the negative items (Q4, Q6, Q7, Q12, Q14, and Q15) were reversed, and total scores were calculated by summing all responses. Previous research using this adapted version showed good reliability with a Cronbach's alpha of .87 (Krellenstein, 1994). Our preliminary analysis showed an acceptable reliability for this questionnaire (α = .76).

Intervention materials

For the intervention of this experiment, we designed a script and storyboard for the instructional videos on the electron transfer chain according to biology standards and the VWO curriculum. Adobe After Effects, Photoshop, and Premier Pro were used to create the educational video. The educational material was designed to teach concepts related to cellular respiration and the mechanisms of the electron transport chain, a dynamic biological process required for the VWO biology curriculum. Oxidative phosphorylation occurs in the inner mitochondrial membrane, where the electron transport chain (ETC) generates a proton gradient, providing energy for the ATP-synthase enzyme to produce ATP. The ETC comprises four membrane complexes (I-IV) that transfer electrons from NADH and FADH2 to molecular oxygen. Feedback from biology teachers and educators facilitated an iterative design process, ensuring the removal of erroneous content.

The electron transfer chain was chosen for its complex spatial organization, allowing us to measure the influence of displaying kinematic changes. The dynamic visualization shows the flow of an electron through the electron transfer chain, from one complex to another, emphasizing the changes and interactions at each step. The static video consists of 63 frames taken from the dynamic visualization. Both videos are 6 minutes and 35 seconds in length and contain the same information, however, the kinematic changes in the static video have to be inferred by changes in the spatial organization of the static images.

Post-test

To examine the learning outcomes, a post-test was conducted, including 14 questions regarding the information about the ETC that was presented in the intervention video. The learning objectives of this post-test were designed to target higher cognitive and knowledge dimensions based on the revised Bloom's taxonomy (Anderson & Krathwohl, 2001). Berney and Bètrancourt (2016) conducted a meta-analysis showing that dynamic visualizations can significantly enhance learning when focusing on higher-order cognitive tasks such as understanding and applying conceptual knowledge. In contrast, dynamic visualizations have minimal benefit over static representations on lower-order tasks like factual recall (McElhaney et al., 2015). The learning objectives were selected to maximize differences in learning outcomes by focusing on higher cognitive and knowledge dimensions. For example, objectives include: “Students can explain the function of mobile electron carriers NADH and FADH2 and specify where they take up and donate electrons,” and “Students can determine how the proton gradient provides the energy for ATP synthesis” (Appendix D). The objectives require students to understand, analyze, and apply conceptual knowledge.

The post-test questions addressed the spatial organization of the ETC and specifically the kinematic changes, providing an evaluation of students’ kinematic mental model (Appendix E). For example, “How is the proton gradient used by the subunits of ATP-synthase to produce ATP?”. Students are required to visualize the kinematic model in their minds in order to answer these questions. Besides the spatial organization, some post-test questions were designed in such a way that required the manipulation of a constructed kinematic mental model (e.g., “How would ATP production change if Co-enzyme Q could no longer transport electrons?”). These questions require students to visualize and manipulate components of the constructed kinematic mental model. To assess the post-test questions, a scoring manual was created, with each open question worth 2 to 4 points, and a maximum score of 34 (Appendix E). To ensure the blind evaluation of the post-test, the group placement and the scores on the dependent variables were concealed during the scoring process of the post-test.

Intervention design

Our experimental design examines the impact of displaying kinematic changes in dynamic visualizations compared to having to infer kinematic changes in static representations. Dynamic visualizations depict transient changes in spatial organization by visualizing changes in direction, velocity, orientation, and acceleration. Changing directions and orientations cannot be illustrated by static representations, but instead have to be inferred from changes in static pictures. Additionally, velocity and acceleration cannot be displayed nor inferred by changes in static representations. The differences in how information about kinematic change is conveyed in the dynamic visualization and static representation videos are summarized in Table 1.

Table 1. Implementation of kinematic change in dynamic visualization and static representation

Kinematic change	Dynamic visualization	Static representation
Direction	Conveys information about changes in the relative positions of components	Changes in relative positions must be inferred from changes in static representations.
Velocity	Conveys information about velocities by visualizing the relative speed and direction of components	Cannot convey relative velocities and cannot be inferred
Orientation	Conveys information about changing orientations	Changes in orientation must be inferred from changes in static representations
Acceleration	Conveys information about acceleration by displaying components' changing velocities relative to other components	Cannot convey accelerations and cannot be inferred

Besides our focus on kinematic changes, we also incorporated multimedia design principles developed by Mayer and Moreno (2002), to enhance the learning effects of visualizations. These principles are grounded in fundamental theoretical frameworks including the cognitive load theory, constructivism learning theory, and the dual-coding theory (Paivio, 1983; Piaget, 1964; Sweller, 1988). Given the role and limitations of working memory, these principles are essential for enhancing the quality of the designs used in educational settings (Mayer & Moreno, 2002). They are intended to lower intrinsic and extrinsic cognitive load, or how information is conveyed and how information is presented, respectively. Lowering cognitive load is intended to increase the ease of integrating information in memory, improving the construction of a mental model (Martin et al., 2021). Important design principles that were implemented in the intervention videos include: 1) coherence; excluding extraneous information, 2) signaling; using cues to guide learners' attention, 3) segmentation; breaking up content into manageable chunks, 4) redundancy; using narration instead of written text, and 5) temporal contiguity; aligning the narration with visual information.

We used a clear iconic representation style for the visual design, using outlines of molecular structures of complexes I-IV and ATP-synthase, sourced from protein structure databases (Figure 4). The structures were marked with distinctive colors to enhance learner differentiation and recall. This iconic representational style aligns with evidence that suggests that abstract representations hinder learning by increasing intrinsic cognitive load (Berney & Bètrancourt, 2016). Additionally, we used a coloring scheme that is commonly used in chemistry education to illustrate the chemical elements, which is intended to lower the intrinsic cognitive load by aligning with prior knowledge (Figure 5) (Corey & Pauling, 1953; Rau, 2015). Furthermore, Berney and Bétrancourt (2016) found that interactive elements like pacing control, subtitles, and pauses negatively impact the learning effectiveness of dynamic visualizations, with system-paced visualizations being more effective. Therefore, we removed the following video settings; pacing controls, pause, subtitles, and quality settings.

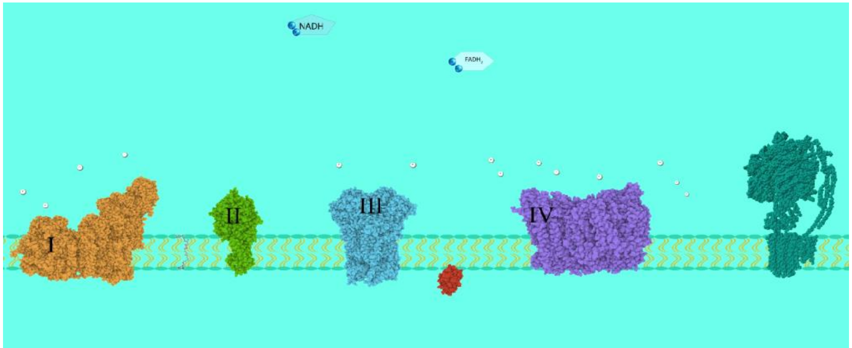


Figure 4. Iconic representation style with distinctive colors.

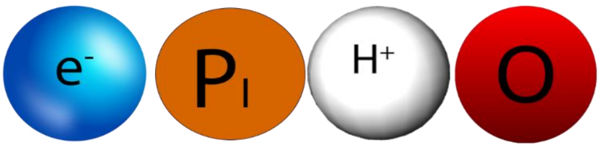


Figure 5. Chemical elements colored according to the Corey-Pauling-Koltun (CPK) used to align with students' pre-knowledge.

While both static and dynamic videos employed general multimedia design principles, certain features were used strategically in the dynamic video but were absent or employed differently in the static version. Cueing features were implemented to optimize the flow and produce logical sequences of events in the dynamic visualization (Table 2). For example, color changes were used to highlight relevant components. Fading was implemented to indicate interactions and movement occurring inside complexes of the ETC, reducing cognitive load by focusing on essential features (Figure 6). Zooming in is used to guide the learner's attention towards important events, and to indicate relative locations in the cellular environments. Additionally, zooming in allowed the removal of extraneous information, further decreasing cognitive load, while zooming out provided context and logical sequences of events. The movement of the electron carrier proteins and zooming in on the complexes happened logically from left to right, so students could process the information sequentially. This reduces cognitive load and facilitates a deeper understanding of the process by carefully constructing a mental model.

Table 2. Implementation of Cueing features in dynamic visualization and static representation

Cueing feature	Dynamic visualization	Static representation
Color changes [Clip color change]	Color change transitions occur smoothly	Color change transitions occur abruptly and have to be inferred
Fading	Smooth transition in transparency	Abrupt transition in transparency
Zooming [Clip zooming in]	Zooming in and out happens smoothly	Zooming in and zooming out happens abruptly and has to be inferred

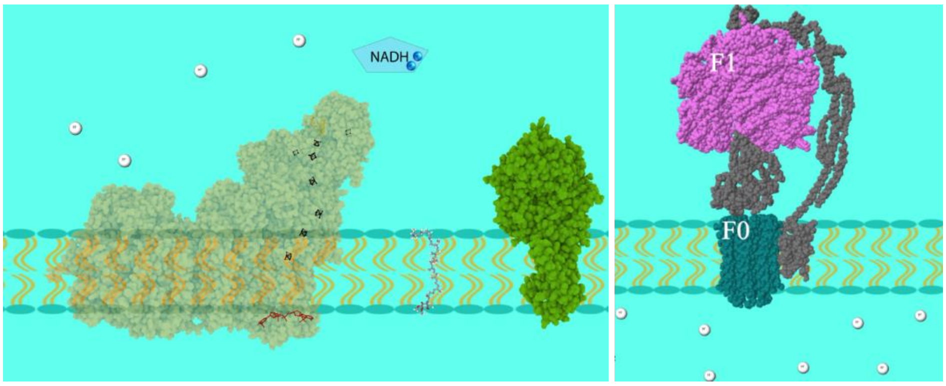


Figure 6. Cueing features (Fading and color changes) implemented, intended to guide students' attention

Data analysis

ETC Survey quality assessment

Before conducting the data analyses, the quality of the ETC post-test items was assessed. This evaluation was necessary because the survey questions were newly developed in this study, to assess specific aspects of kinematic change and the spatial organization of the ETC. Given that the survey was new, and the psychometric properties have not been previously validated, it was crucial to rigorously evaluate the items to ensure the accuracy and reliability in measuring the intended constructs. Using classical test theory within the framework of item response theory, the item difficulty index (p_i) and item discrimination index were analyzed, using a threshold of $p_i \leq 0.5$ (Reynolds & Livingston, 2013). Although more challenging questions ($p_i > 0.5$) might regularly still be retained in educational testing settings, research suggests that including items with extreme difficulty can diminish the overall reliability of a test by contributing minimally to the measurement of the intended construct (Crocker & Algina, 1986). Thus, the untested nature of this survey necessitated the implementation of the 50% cut-off to ensure only the most reliable items were included. The response distribution was categorized into; no answer, no points, and one or more points (Table 3). The combined percentage of missing responses and entirely incorrect answers was used to evaluate the $p_i \leq 0.5$ threshold. Items Q2A, Q3A, and Q6B exhibited a $p_i > 0.5$, indicating high difficulty levels and potentially low discrimination (Table 3). Consequently, to enhance the reliability and validity of the ETC survey, Q2A, Q3A, and Q6B we excluded from further analysis.

Table 3. ETC post-test questions quality assessment

Questions	No Answer	0 points	1 or more point(s)	No Answer + 0 points
Q1A	11%	5%	84%	16%
Q1B	14%	14%	73%	27%
Q2A	14%	54%	32%	68%
Q2B	8%	19%	73%	27%
Q3A	16%	35%	49%	51%
Q3B	32%	11%	57%	43%
Q4A	5%	27%	68%	32%
Q4B	14%	8%	78%	22%
Q5A	11%	24%	65%	35%
Q5B	19%	27%	54%	46%
Q6A	0%	16%	84%	16%
Q6B	30%	32%	38%	62%

Note. The red values represent questions with an item discrimination of $p_i \leq 0.5$

Assumption checks

Before conducting the analyses, we examined several assumptions. First, we assessed the normal distribution of variables using histograms. To ensure the integrity of the data, we scrutinized for the absence of outliers utilizing standardized residuals (Min. -3.3, Max. 3.3), Mahalanobis Distance (<14), and Cook's Distance (<1) (Field, 2018). Autocorrelation was assessed via Durbin-Watson (DW), aiming for a value close to 2 (Field, 2018). Additionally, multicollinearity was evaluated through Tolerance (>.20) and the variance inflation factor (VIF) (<10) (Field, 2018). To ensure even dispersion of the data within the sample, homoscedasticity was examined by visually inspecting a scatter plot. Furthermore, to verify the stratified randomization based on the biology grade, we conducted an independent samples t-test to check the equal distribution of biology grades across the intervention groups (ED vs. CS). Additionally, to assess the comparability and equal distribution of the independent variables between the intervention groups, two separate independent samples t-tests were conducted for the IDQ-IHS and VVIQ.

T-test

We analyzed the difference between the ED and CS groups on the learning outcome (hypothesis 1), using an independent samples t-test with Levene's test for homogeneity of variances. Given the sample size, we interpreted the effect size using Hedge's g (Field, 2018).

Moderation analysis

The moderating hypotheses were examined using a moderation analysis conducted with the PROCESS function in IBM SPSS Statistics 29. A Bootstrap Sample of 5000 was employed to generate a 95% Confidence Interval (Hayes, 2022). We used a multivariate analysis with the PROCESS function, utilizing centering techniques to mitigate multicollinearity. The analysis considered significance ($p < .05$), effect size (b), and explained variance (R^2). For hypothesis 3, a moderated moderation PROCESS analysis was performed, with visual cognitive style as the primary moderator and visual imagery vividness as the secondary moderator (Hayes, 2022). Using the moderated moderation PROCESS analysis is beneficial, as it examines the effect of the primary moderator independently of the secondary moderator and then analyzes the effect when the secondary moderator is included (Hayes, 2022).

Results

Preliminary analyses

The first assumption check showed one outlier on all scales (IDQ-IHS, VVIQ, ETC). After the removal of the outlier, the IDQ-IHS, VVIQ, and ETC survey showed a normal distribution (Standardized Residuals Min. = -2.066, Max. = 1.899; Cook's Distance = .265; Mahalanobis Distance = 7.146). The Durbin-Watson indicated the absence of autocorrelation (DW = 2.05), and the Tolerance (.762) and VIF (1.31) values confirmed the absence of multicollinearity. Scatter plots of residuals for ETC, IDQ-IHS, and VVIQ scores indicated homoscedasticity within the sample.

Additionally, we conducted an independent samples t-test to verify that the intervention groups (ED vs. CS) did not differ significantly in terms of independent variables. The results showed no significant difference between the intervention groups on the IDQ-IHS ($p = .355$), VVIQ ($p = .620$), and the Biology grades ($p = .514$).

Correlations

Table 4 shows the mean scores and the correlation analysis between the IDQ-IHS, VVIQ, and the ETC survey. The IDQ-IHS and VVIQ were significantly correlated ($r = .488$, $p < .001$). However, there was no significant correlation between the IDQ-IHS and ETC scores ($r = -.015$, $p = .933$), nor between the VVIQ and ETC scores ($r = -.068$, $p = .712$).

Table 4. Mean scores and correlations of IDQ-IHS & VVIQ and ETC scores

	M	SD	IDQ-IHS	VVIQ
IDQ-IHS	3.78	.39		
VVIQ	3.77	.50	.488**	
ETC Survey	10.62	4.29	-.015	-.068

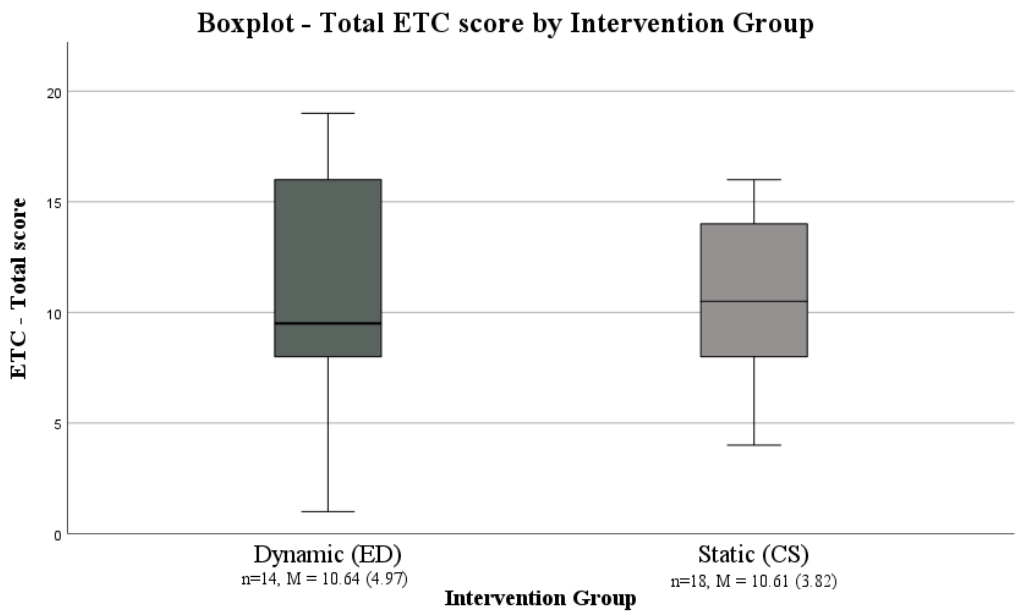
** p < .05, ** p < .01*

Primary analyses

Hypothesis 1

To test hypothesis 1, the difference between the ED and CS groups was analyzed using an independent samples t-test. Contrary to our hypothesis, no significant difference in ETC post-test scores was found between the ED and CS groups (p = .984) (Figure 7).

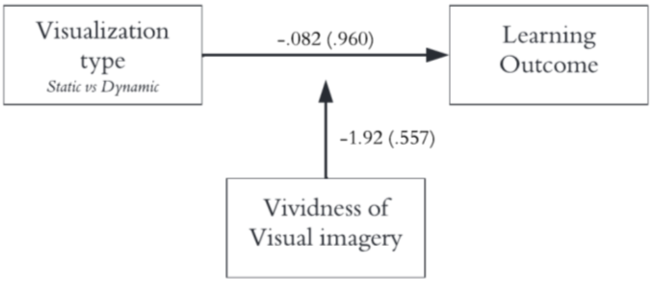
Figure 7. Results of the independent sample t-test for hypothesis 1



Hypothesis 2

The second hypothesis was tested using a PROCESS moderation analysis. Contrary to the hypothesis, there was no significant main effect of the visualization type on the learning outcome (b = -.082, SE = .1.60, t = -.051, p = .960), as well as no significant effect of the vividness of visual imagery on the learning outcome (b = -.775, SE = 1.64, t = -.473, p = .640). Furthermore, the interaction between visualization type and vividness of visual imagery was non-significant (b = -1.92, SE = 3.22, t = -.595, p = .557), indicating that the differences in learning outcome between the ED and CS group was not moderated by the vividness of visual imagery (Figure 8).

Figure 8. Results of PROCESS moderation analysis for hypothesis 2

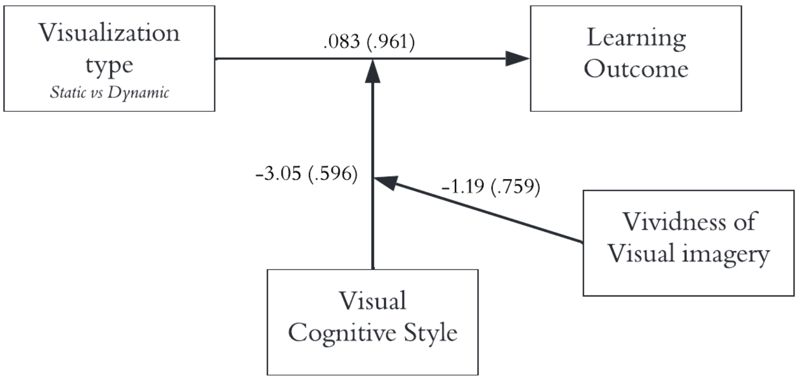


Note. b values of hypothesized effects, p-values are shown between parenthesis (all p > .05)

Hypothesis 3

A PROCESS moderated moderation analysis was performed for hypothesis 3 (Figure 9). Contrary to our hypothesis, we did not find a significant main effect of visual cognitive style on the learning outcome (b = 1.16, SE = 2.69, t = .430, p = .671). In addition, there was no significant moderating effect of visual cognitive style on the learning effect of different visualization types (b = -3.05, SE = 5.68, t = -.537, p = .596). Consequently, there was no significant moderating effect of the vividness of visual imagery on the moderation (R^2 *changed* = .025, *95% CI* [-9.09 - 6.71], *F* = .337, p = .717).

Figure 9. Results of PROCESS moderation analyses for hypothesis 3



Note. b values of hypothesized effects, p-values are shown between parenthesis (all p > .05)

Exploratory analysis

Biology Grade

Several exploratory analyses were conducted to investigate alternative explanations for the null findings. One covariate considered was the students' biology grades. This covariate was accounted for prior to the experiment by dividing the sample based on biology grades, ensuring that both groups had a similar average to control for the possible influence of prior knowledge. Although the biology grades and ETC scores did not significantly differ between the intervention groups, a significant relationship was found between ETC scores and biology grades (r = .472, p < .01). However, no significant relationships were found between biology grades and either cognitive style or vividness. An ANCOVA was conducted to control for the biology grade in assessing the differences between the ED and CS conditions on learning outcome. When including biology grade in the ANCOVA, results showed that this covariate had a significant effect on the ETC score (*F*(1, 29) = 8.14, p <.01, partial η^2 = .225). This indicates that including the biology grade as a covariate helps to explain some variability of the learning outcome. However, the difference between the intervention groups remained non-significant (*F*(1, 29) = .101, p = .753), meaning there is no difference between the learning outcomes of the ED and CS groups even after controlling for biology grades.

IDQ-IHS Questionnaire

The psychometric properties of the IDQ-IHS questionnaire revealed several ambiguities. Although the overall Cronbach's Alpha indicated acceptable reliability for the questionnaire ($\alpha = .76$), the inter-item correlations revealed that only a few items within the IDQ-IHS were significantly correlated with other items on the scale. Moreover, some items exhibited significant negative correlations with other items on the IDQ-IHS scale, suggesting potential issues with the psychometric integrity of the questionnaire in this sample. To further examine these issues and to determine the dimensionality of the items within this study, an exploratory factor analysis (EFA) was done to identify the underlying factor structure. The EFA was performed with a minimum residual extraction with Oblimin rotation, and factors were retained based on an Eigenvalue greater than 1. The analysis identified two factors accounting for 38.1% of the explained variance. While the Sphericity (Barlett's Test) shows to be significant ($X^2(105) = 210$, $p <.001$), indicating that the data was suitable for the factor analysis, the overall model shows a poor fit (RMSEA = .0917 [.023-.150], TLI = .664, $X^2(76) = 98.9$, $p = .04$). The factor loadings can be found in Appendix F. These findings should be taken into consideration when interpreting the primary results of this study, as they identify psychometric issues of the IDQ-IHS in the current sample.

Discussion

The past decade has played a significant role in the development of innovative educational materials, specifically due to the rapid and forced adaptions during the COVID pandemic. This movement to create innovative educational materials calls for scientific research, to design these new materials based on empirical evidence. Especially in some fields, like biology education, computational tools have the potential to significantly enhance learning. One strategy that gained considerable attention is dynamic visualization. However, the lack of consistent empirical evidence supporting effective implementations of visualizations suggests many factors influence learning with visuals (Ploetzner et al., 2020; Lowe & Ploetzner, 2017). The interplay between instructional designs and personal characteristics that influence learning has gained considerable attention in the last decade. This study investigated the potential cognitive fit of kinematic changes, visual cognitive style, and vividness of visual imagery on the learning effect of different types of visualizations.

Dynamic visualizations facilitate the construction of kinematic mental models. They depict micro changes in chronological order, helping students construct mental representations of objects and spatial relations as sequential events. Students use these kinematic mental models as tools, imagining the sequence of events and manipulating the spatial organization of objects to solve problems. Forming these mental models requires the creation of visual representations in the mind. This ability, known as visual imagery, differs from person to person. These differences in the vividness of visual imagery may affect how easily students generate and manipulate these mental model representations, potentially moderating the learning effects of different visualization types. It remains unclear whether an aptitude-treatment interaction (ATI) exists between vividness and type of visualization. We conducted an experiment where participants viewed an educational video about the electron transport chain (ETC), presented either as static representations or a dynamic visualization focusing on kinematic changes. We aimed to determine whether the educational effectiveness of dynamic visualizations is due to their depiction of micro changes in spatial organization. Additionally, this study explored whether an ATI exists between vividness scores (VVIQ), habitual use of visual imagery scores (IDQ-IHS), and the type of visualization (dynamic or static). Our results could inform the design of visual educational materials, accounting for the vividness of visual imagery and cognitive styles.

Interpretation

Contrary to our expectations, the group that watched the dynamic visualization of the ETC process, did not score significantly higher on the ETC post-test compared to the group that watched the static representation. Our results are in contrast with the findings of Ploetzner et al., (2020) who identified kinematic change as a moderating variable. Our findings align with the results from Berney & Betrancourt (2016), which showed that 59.3% of the pair-wise comparisons found no significant difference between static and dynamic, suggesting that dynamic visualizations are not universally superior to static ones. The hypothesis that dynamic visualization displaying kinematic change would enhance learning outcomes when learning dynamic biological processes was not supported. The drawback of static compared to dynamic visualization, is the lack of continuous change and the inability to use continuous dynamics to construct detailed kinematic mental models. However, research indicates that inferring changes in spatial organization can improve the retention and recollection of spatial information (Leahy & Sweller, 2004; Leahy & Sweller, 2008). This imagination effect that occurs when students have to infer changes themselves may explain our insignificant results, and can potentially be attributed to the effective implementation of design principles and features (Mayer and Moreno, 2002). We utilized multimedia design principles such as coherence, temporal contiguity, segmentation, redundancy, and signaling principles. Additional cueing features were used to lower extrinsic and intrinsic cognitive load. Segmenting the content into manageable chunks, and guiding attention using zooming, fading, and color changes may have adequately lowered intrinsic cognitive load. This may have enabled students to infer kinematic changes in the static video without cognitive overload, mitigating the advantages of dynamic visualizations. We made sure that the information presented in both videos remained equal. In other words, all aspects of kinematic motion could be seen in the dynamic video and, except for velocity and acceleration, inferred by static pictures alone. All 63 static frames showed important changes and interactions relevant to learning. Our results indicate that the educational benefit of dynamic visualizations is not superior to static when the cognitive load is adequately reduced, and all information relevant to learning is available and inferable.

Furthermore, the equal distribution but low overall scores of learning outcomes between static and dynamic may be attributed to the influence of prior knowledge and domain jargon. Biology education includes many definitions and jargon necessary to comprehend the underlying process and interactions. This association between visual and verbal stimuli is error-prone and might introduce excessive cognitive load when prior knowledge is insufficient. Research indicates that prior knowledge significantly influences the effectiveness of visualizations by facilitating the integration of new information into existing mental models (Höffler, 2010; McElhaney et al., 2015). We found a significant correlation between average biology grades and ETC scores, indicating a positive relationship between biology grades and learning outcome. This could potentially mean that sufficient prior knowledge and a well-thought-out explanatory narration influence learning outcomes more than the type of visualization does.

As for the second hypothesis, contrary to expectations, no significant relationship between the vividness of visual imagery and the learning outcome was found, indicating that vividness of visual imagery does not influence learning outcomes when learning with visuals. Additionally, there was no moderating effect of vividness on the differences between static and dynamic visualizations in learning outcome. This is in contrast to the findings of Pearson (2014) who found that vivid imagery is associated with an increased working memory capacity. Increased visual working memory capacity could enable students to keep more visual elements in working memory, allowing them to mentally manipulate more components of a mental model. The post-test questions were specifically designed to assess the spatial relations and interactions of components of the ETC. An example question from the ETC survey is, “How would ATP production change if Co-enzyme Q could no longer transport electrons?”. To answer these questions, students had to use constructed mental models and mentally manipulate elements of the ETC. These results seem to suggest that the ability to clearly perceive the spatial organization of a dynamic process in the mind’s eye does not influence the construction of a kinematic mental model or the subsequent manipulation of its components.

Furthermore, the absence of the ATI between vividness and visualization type suggests that having different levels of vividness does not influence the learning effect of the visualization type. However, these insignificant results do not necessarily mean that there were no interactions. The enhancing and compensating effects might have balanced each other out, indicating that both compensating and enhancing effects of vividness on learning with dynamic visualization could exist. The ability-as-compensator hypothesis states that individuals with low vividness cannot infer the changes in static representations. Therefore, students with low vividness benefit more from dynamic visualization, as they serve as a template for mental model construction. Conversely, the ability-as-enhancer proposes that to benefit from dynamic visualization, a certain level of vividness is necessary to deal with the additional cognitive load associated with dynamic visualizations. However, since our results indicate no relation between vividness and learning outcome, an ATI between visualization type and vividness cannot be assumed.

Opposed to the third hypothesis, no significant relationship was found between visual cognitive style and the learning outcome, indicating that differences in students' visual processing strategies do not influence learning outcomes when learning with visuals. It has been shown that visualizers and verbalizers interact differently with visual information, however, the only notable difference between visualizers and verbalizers in how they interact with visual information is that verbalizers focus on irrelevant visual details significantly more (Höffler et al., 2017; Koć-Januchta et al., 2017, 2019). The insignificant correlation can be explained by the implemented design principles and cueing features. Cueing features, such as zooming, fading, and color change, were implemented to guide students' attention to important events. These features might have diluted this difference by guiding verbalizers' attention to critical events, resulting in an insignificant correlation.

We found a significant correlation between visual cognitive style and vividness. However, there was no significant correlation between visual cognitive style and learning outcomes when learning with visuals. Our results are in line with the findings of Massa & Mayer (2006) that suggest no ATI between verbalizers and visualizers exists when learning with different modes of information. In contrast, Koć-Januchta et al. (2017) found a moderating effect of cognitive style on learning outcomes when comparing text-based and visual information. However, this study only investigated the ATI between the level of visual cognitive style and static and dynamic visualizations. Our results can be explained by the differences between static and dynamic visualizations not being pronounced enough for this ATI to become noticeable. Our results indicate no influence of habitual use of visual imagery on the learning effect of different visualization types (Höffler et al., 2017; Koć-Januchta et al., 2017, 2019).

Taken together, our findings seem to suggest that dynamic visualizations, displaying kinematic changes, are not superior to static representations when learning dynamic biological processes. Our findings indicate that the creation of a kinematic mental model is not necessarily improved after being exposed to visuals of dynamics compared to static images. Students having to infer spatial changes may have improved learning outcomes, similar to seeing these dynamic changes. This might be because the cognitive load in the static video was adequately lowered through design principles and cueing features, allowing all students, despite their cognitive differences, to infer changes without cognitive overload. Furthermore, the insignificant correlations between learning outcome, vividness, and cognitive style indicate that the creation and manipulation of kinematic mental models is not influenced by visual processing strategies or the vividness of visual imagery.

Our findings align with those of Kay et al. (2024), who found that individuals with aphantasia can still complete a mental rotation task. The mental rotation test is an indicator of spatial abilities and requires the manipulation of objects in the mind. We also assessed spatial abilities by carefully constructing the post-test items to require kinematic model manipulation. Recently, Speed and McRae (2024) found that control participants and aphantasics showed similar results using mental simulations in problem-solving tasks. Their results indicate that using mental simulations during problem-solving does not require the subjective perception of objects in the mind. These surprising results suggest that spatial manipulation and visual imagery are separate cognitive processes that do not rely on each other. This is in line with the suggestions of Bates and Farran (2021), who posit that alternative strategies, other than visual imagery, may explain the disconnection between vividness and visual working memory capacity. It might be that during problem-solving tasks that require the manipulation of spatial organization, despite being a vivid visualizer, students use spatial strategies instead of visual imagery as it proves the most efficient processing route. It could be, that individuals still form visual images during spatial tasks, but that visual imagery is not the dominant cognitive process that solves the problem. Our results support the growing body of evidence suggesting alternative strategies, other than visual imagery, for problem-solving tasks involving spatial manipulations (Kay et al., 2024; Keogh et al., 2021; Wicken, et al., 2021; Keogh & Lau, 2024; Pearson & Keogh, 2019).

Limitations, Strengths, and Future Research

When interpreting our findings, several limitations have to be taken into account. First, in biology education, conveying all necessary information requires the combination of visual stimuli and verbal explanations. This is crucial for understanding the mechanisms of the ETC. The advantages of kinematic change might not have been fully assessed because the questions focused on specific components. Simply recalling micro changes was insufficient; students needed to associate the verbal terms with visual stimuli and then visualize the interactions, which increased the likelihood of errors. Drawing individual components, interactions, or kinematic changes might prove a better method for assessing kinematic changes (Ploetzner et al., 2020).

Anticipating that average biology grades might influence learning outcomes, we used stratified randomization based on average biology grades to minimize potential biases. We found a significant correlation between average biology grades and learning outcome. This would imply that average biology grade is a confounding variable and positively influences learning outcomes, suggesting that prior knowledge affects the learning outcomes more than the type of visualizations does. However, since the average biology grade may not accurately reflect prior knowledge, future research should consider grouping participants assessed through a pre-test, rather than average biology grades, to better control for this potential confounder. Alternatively, future studies could investigate the beneficial impact of learning specific prior knowledge related to the components and interactions of a dynamic process before learning from visualizations.

Another limitation is the duration of the educational video. Although vividness correlates with visual working memory capacity, research indicates no relationship between VVIQ vividness scores and visual short and long-term memory capacity and performance (Tabi et al., 2022; Thorudottir et al., 2024). This suggests that high vividness does not necessarily equate to better integration of visual information into memory. A larger visual working capacity might be beneficial for utilizing visual information in visual working memory, but this first requires effective uptake of information. Since the intervention video was viewed only once and lasted 6 minutes and 35 seconds, short-term memory constraints might have hindered the proper integration of visual information. Despite the post-test questions being ordered chronologically to mitigate this issue, the videos' duration, combined with its complexity, may have negatively affected the results.

Given that this study focused on exploring whether the vividness of visual imagery moderates learning outcomes depending on representation type, it was essential to include the IDQ-IHS alongside the VVIQ. While the VVIQ measures the clarity and vividness of one's visual imagery, it does not assess whether an individual habitually uses visual imagery in cognitive tasks. The IDQ-IHS fills this gap by measuring the frequency and context where visual imagery is used, particularly in problem-solving tasks critical to learning processes. The combination of the VVIQ and IDQ-IHS allowed this experiment to rigorously assess the vividness of visual imagery and the practical use of visual imagery in educational settings. However, the IDQ-IHS used to measure the habitual use of visual imagery showed ambiguous results in our sample. The exploratory analysis revealed poor inter-item correlations, with some items showing significant negative correlations. This suggests that, in our sample, the IDQ-IHS did not adequately measure the intended constructs, indicating poor validity. Massa & Mayer (2006) criticized using questionnaires to gauge cognitive capacities and behaviors, instead they propose a combination of subjective and objective measurements. Using objective measurements to corroborate the results of self-report questionnaires has the potential to resolve these ambiguities.

Future research could use eye-tracking data to explore students' gaze behaviors while learning from static or dynamic visualizations. This could potentially reveal how a visual cognitive style influences attention to different visual stimuli (Koć-Januchta et al., 2017). This data could reveal how kinematic changes impact student focus and learning. Additionally, eye-tracking data may show whether cueing features and design principles significantly improve learning with visuals by guiding attention and lowering cognitive load. The VVIQ self-assessment scores could be corroborated by objective measurements in future research. It is possible to objectively measure an individual's vividness of visual imagery (Xu Cui et al., 2007). This can be done by measuring physiological aspects using the binocular rivalry technique or the pupillary light response (Kay et al., 2022). Additionally, brain imaging techniques can decisively measure whether students use visual imagery in spatial tasks requiring spatial manipulation (Keogh & Pearson, 2024).

Given the findings, future research may explore how repeated exposures and different instructional contexts impact the effectiveness of visualizations. Studies could investigate whether multiple, shorter sessions of dynamic visualizations, focused on kinematic change, yield better results than a single, longer exposure. Additionally, this study highlights the importance of considering alternative cognitive strategies. Research is needed to examine the influence of vividness on various types of visual tasks, beyond spatial organization and manipulation, in order to determine its broader educational implications. For instance, spatial strategies might be more effective than visual imagery in certain contexts. Future studies could investigate the impact of different instructional designs and learning demands on various cognitive styles and strategies, providing a more nuanced understanding of how to optimize learning with visuals.

Implications

The lack of significant differences in learning outcomes between dynamic and static visualizations challenges the assumption that dynamic visualizations are inherently superior. This indicates that other factors, such as the clarity of explanations and the integration of visual aids with verbal instructions, may play a more critical role in understanding dynamic biological processes. Educators and instructional designers should reconsider an automatic preference for dynamic visualizations. Instead, focusing attention on creating clear, concise, and well-integrated instructional materials by focusing on the context, content, and design features, may be more effective for learning with visuals. Reducing cognitive load and aligning the content with prior knowledge may be more beneficial than simply using dynamic displays. Furthermore, when teaching about the spatial organization of dynamic processes, educators should reconsider using design features intended to facilitate visual imagery strategies.

Conclusion

To conclude, a beneficial effect of displaying continuous kinematic changes in visualizations is not supported in this current study. Influences of vividness and visual cognitive style on learning with visualizations were also not found. However, we did find a positive relation between average biology grade and learning outcome, indicating a positive influence of prior knowledge on learning with visualizations. The lack of differences between visualization types substantiates the importance of effective implementation of design principles and aligning the content with prior knowledge. Additionally, The absence of influences from visual imagery vividness and visual cognitive style on learning with visualizations indicate that the construction and manipulation of mental models is not influenced by visual imagery or visual cognitive strategies. These findings suggest that alternative cognitive processing routes, other than visual imagery, responsible for spatial manipulation. The current study underlines the notion that research investigating cognitive processes and aptitudes involved in learning with visuals might one day show us how the optimal visualization looks like.

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Appendix

A. Informed consent

Geachte lezer,
Alvast heel erg bedankt voor je deelname aan dit onderzoek!

Waarover gaat het
Vanuit de afdeling Freudenthal Instituut van de Universiteit Utrecht verrichten we onderzoek naar inbeeldingsvermogen, leeropbrengsten en het gebruik van animatie. Dit onderzoek kan heel informatief zijn voor verdere theoretische kennis en ontwikkeling van onderwijsvormen. De gegevens van dit onderzoek zullen worden gebruikt voor een masterthesis en kunnen later ook uitmonden in een publicatie van een wetenschappelijk artikel.

Hoe het onderzoek wordt uitgevoerd en wat van jou als participant verwacht wordt
In dit onderzoek worden eerst wat achtergrondgegevens gevraagd zoals geslacht, leeftijd, nationaliteit, biologie cijfer en cognitieve invloeden. Daarna vragen we je een aantal vragenlijsten in te vullen rond inbeeldingsvermogen. Dit wordt gevolgd door een educatieve video, waarna je een aantal vragen over de video zult beantwoorden. Deelname aan het onderzoek duurt ongeveer 30 minuten.

Mogelijke indirecte voor- of nadelen
Het invullen van deze vragenlijsten wordt naar ons inschatten niet als belastend ervaren.

Vrijwilligheid deelname
Deelname aan het onderzoek is volledig vrijwillig. Je kunt op elk gewenst moment stoppen zonder opgave van redenen en zonder consequenties. Informatie die je geeft voordat je stopt, wordt wel verzameld en in het onderzoek gebruikt, tenzij je expliciet aangeeft dit niet te willen.

Vergoeding
Voor dit onderzoek wordt geen vergoeding gegeven.

Persoonsgegevens & Privacy
De data worden vertrouwelijk behandeld, d.w.z. geanonimiseerd opgeslagen volgens de hoogste beveiligingsnormen en alleen toegankelijk voor de betrokken onderzoekers. De weinige persoonsgegevens die gevraagd worden (i.e., leeftijd, gender, etc.) zijn niet naar jou als persoon te herleiden. Uw gegevens zullen voor maximaal 10 jaar bewaard worden. Dit alles volgens de daartoe bestemde richtlijnen van de Vereniging van Universiteiten (www.vsnu.nl). Meer informatie over privacy kun je lezen op de website van de Autoriteit Persoonsgegevens:
https://autoriteitpersoonsgegevens.nl/nl/onderwerpen/avg-europese-privacywetgeving

Onafhankelijk contactpersoon en klachtenfunctionaris
Voor vragen of opmerkingen over het onderzoek kun je contact opnemen met thesis student Ruben van Swieten (r.r.vanswieten@students.uu.nl). Als je een officiële klacht wilt indienen kun je mailen naar: klachtenfunctionaris-fetcsowet@uu.nl

Toestemmingsverklaring
Hierbij verklaar ik de informatiebrief m.b.t. het onderzoek rond “inbeeldingsvermogen en leeropbrengsten” gelezen te hebben, voldoende geïnformeerd te zijn en akkoord te gaan met deelname aan het onderzoek.

- ☐ Ik ga akkoord

B. Excluding criteria and demographic questions

Wat is je leeftijd? (graag invullen als getal)

...

Wat past het best bij jou?

- Man
- Vrouw
- Anders, namelijk..
- Deel ik liever niet

In welke klas zit je?

...

Wat is je gemiddelde cijfer voor biologie van het afgelopen jaar? *(graag invullen als getal met 1 getal achter de komma)*

...

Is een van onderstaande van toepassing op jou?

- Kleurenblind
- Verziendheid / bijziendheid zonder correctie (geen bril of lenzen)
- Andere visuele beperking, namelijk ...
- Geen van bovenstaande

Is een van onderstaande van toepassing op jou?

- ADHD/ADD
- Autisme
- Dyslexie
- Dyscalculie
- Anders, namelijk..
- Zeg ik liever niet
- Geen van bovenstaande

C. Questionnaires

C1. Vividness of Visual Imagery Questionnaire (VVIQ)

Dutch translation

Introductie
Visuele voorstellingen gaan over hoe goed je dingen in je hoofd kunt zien, alsof je een plaatje in je gedachten hebt. Mensen verschillen veel in hoe helder en sterk deze beelden voor hen zijn, en dat vinden psychologen heel interessant.

Het doel van deze test is om uit te vinden hoe levendig jij dingen kunt voorstellen. Bij de vragen zul je misschien beelden in je hoofd krijgen. We vragen je om te beoordelen hoe scherp en helder elk beeld is, gebruikmakend van de schaal van 5 punten hieronder. Als je beeld bijvoorbeeld "vaag en wazig" is, geef het dan een 4. Geef antwoord door het vakje met de juiste beoordeling aan te klikken.

Schaal
1. Zeer scherp en zo levendig als normaal zicht
2. Redelijk scherp en levendig
3. Enigszins scherp
4. Vaag en wazig
5. Ik zie geen beeld, ik 'weet' alleen dat ik eraan denk

Gebruik deze schaal bij elke vraag om te beslissen hoe helder elk beeld is. Probeer elke vraag los van de anderen te beantwoorden. Tijdens het inbeelden kan je je ogen open houden of sluiten.

Landschap
Denk aan een landschap met bomen, bergen en een meer. Ga bij de volgende stellingen bij jezelf na hoe scherp en levendig de beelden zijn die bij je op komen.

1. De contouren van het landschap

1	2	3	4	5
○	○	○	○	○

2. De kleuren en vormen van de bomen

1	2	3	4	5
○	○	○	○	○

3. De kleur en vorm van het meer

1	2	3	4	5
○	○	○	○	○

4. Een harde wind blaast door de bomen en zorgt voor golven op het meer

1	2	3	4	5
○	○	○	○	○

Vrienden

Denk aan een vriend die je vaak ziet (maar nu niet aanwezig is). Ga bij de volgende stellingen bij jezelf na hoe scherp en levendig de beelden zijn die bij je op komen.

1. De exacte contour van het gezicht, hoofd, schouders en lichaam

1	**2**	**3**	**4**	**5**
○	○	○	○	○

2. Karakteristieke hoofdhoudingen, lichaamshoudingen

1	**2**	**3**	**4**	**5**
○	○	○	○	○

3. De houding en stapgrootte tijdens het lopen

1	**2**	**3**	**4**	**5**
○	○	○	○	○

4. De verschillende kleuren in de kleding die hij/zij draagt

1	**2**	**3**	**4**	**5**
○	○	○	○	○

Opkomende zon

Denk aan een opkomende zon. Ga bij de volgende stellingen bij jezelf na hoe scherp en levendig de beelden zijn die bij je op komen.

1. De zon komt op boven de horizon in een mistige lucht

1	**2**	**3**	**4**	**5**
○	○	○	○	○

2. De lucht wordt helder en omringt de zon met blauw

1	**2**	**3**	**4**	**5**
○	○	○	○	○

3. Wolken. Een storm waait over met bliksemschichten

1	**2**	**3**	**4**	**5**
○	○	○	○	○

4. Er ontstaat een regenboog

1	**2**	**3**	**4**	**5**
○	○	○	○	○

Winkel

Denk aan de voorkant van een winkel waar je vaak komt. Ga bij de volgende stellingen bij jezelf na hoe scherp en levendig de beelden zijn die bij je op komen.

1. Het aanzicht van de winkel vanaf de overkant van de straat

1	**2**	**3**	**4**	**5**
○	○	○	○	○

2. Een etalage met de kleuren, vormen en details van individuele producten

1	**2**	**3**	**4**	**5**
○	○	○	○	○

3. De kleur, vorm en details van de deur

1	**2**	**3**	**4**	**5**
○	○	○	○	○

4. Je gaat naar binnen. De servicebalie medewerker helpt je en er wordt geld overhandigd

1	**2**	**3**	**4**	**5**
○	○	○	○	○

C2. Individual differences questionnaire on habitual imagery strategies (IDQ-HIS)

Dutch translation

Introductie
Deze vragenlijst is bedoeld om er achter te komen of je inbeelding gebruikt bij het oplossen van problemen. Geef alsjeblieft antwoord op de vragen door 1 aan te klikken als je het erg oneens bent met de stelling, of een 5 als je het eens bent, of een waarde ertussenin om een tussenliggende staat van oneens en eens zijn aan te geven.

Schaal
Erg mee oneens (1)
Oneens (2)
Niet mee eens of oneens (3)
Eens (4)
Erg mee eens (5)

Items
1. Ik gebruik vaak mentale beelden of plaatjes om mij dingen te herinneren.
2. Door mentale plaatjes van de elementen van een probleem te gebruiken, kan ik vaak tot een oplossing komen.
3. Mijn denken bestaat vaak uit mentale beelden of plaatjes
4. Ik vind het moeilijk om een mentaal beeld van iets te vormen.
5. Ik gebruik vaak mentale plaatjes om problemen op te lossen
6. Wanneer ik me een scène herinner, gebruik ik verbale beschrijvingen in plaats van mentale plaatjes.
7. Ik gebruik nooit mentale plaatjes of beelden bij het proberen op te lossen van problemen.
8. Ik geniet vaak van het gebruik van mentale plaatjes om te dagdromen.
9. Ik kan mijn ogen sluiten en gemakkelijk een scène voorstellen die ik heb meegemaakt
10. Ik denk dat de meeste mensen in termen van mentale plaatjes denken, of ze zich daar nu volledig van bewust zijn of niet.
11. Ik kan gemakkelijk bewegende objecten in mijn geest voorstellen.
12. Ik vorm geen mentaal beeld van mensen of plaatsen wanneer ik over hen lees.
13. Wanneer iemand iets beschrijft dat hem of haar is overkomen, betrap ik mezelf er soms op dat ik de gebeurtenissen levendig voor me zie.
14. Ik heb slechts vage visuele indrukken van scènes die ik heb meegemaakt.
15. Luisteren naar iemand die zijn ervaringen vertelt, wekt meestal geen mentale beelden op van de beschreven incidenten.

D. Learning objectives (Dutch)

Leerdoelen:
1. Leerlingen kunnen het doel van dissimilatie uitleggen en de rol van oxidatieve fosforylering.
2. Leerlingen kunnen de locatie waar dissimilatie gebeurd benoemen en ook de locatie van de elektronentransportketen.
3. Leerlingen kunnen uitleggen wat de functie van de elektronendrager moleculen NADH en FADH2 zijn en waar NADH en FADH2 de elektronen naartoe brengen en elektronen vandaan halen.
4. Leerlingen kunnen uitleggen hoe de losgekomen elektronen verspringen in de complexen en bij elke sprong energie verliezen en dat dit zorgt voor het pompen van H+ ionen in de intermembraan ruimte.
5. Leerlingen kunnen beschrijven hoe de protonengradiënt tussen de membraan ruimtes tot stand komt en hoe dit protongradiënt de ATP-synthese aandrijft.
6. Leerlingen kunnen de structuur (F0 en F1 sub eenheid) van ATP-synthase beschrijven en de functie van de sub eenheden bij het aanmaken van ATP uit ADP en fosfaat uitleggen.

E. ETC survey post-test scoring manual

Scoring manual ETC kinematic change
Scoring is based on reproduction of movement of components.

Question 1: Role and Function of Complex II (Total: 5 points)

a. Leg uit wat de rol van Complex II is in de elektronen transport keten.

- **1 point**: Identifies that Complex II accepts electrons/ is a starting complex.
- **1 point**: States that Complex II transfers electrons

Additional Detail:

- **1 point**: Notes that Complex II is also part of the citric acid cycle as the succinate dehydrogenase complex.

b. Wat doet complex II niet wat de andere complexen wel doet?

-
- **2 point**: Identifies that Complex II does not pump protons across the membrane.
- **or** Compares Complex II's function with Complexes I, III, and IV.

Question 2: Impact of Dysfunctional Complex I on Electron Transport and ATP Production (Total: 6 points)

a. Hoe wordt het transport van elektronen door de elektronentransport keten aangetast als Complex I niet meer werkt?

- **2 points**: Describes how electron transport is disrupted as electrons cannot enter the chain.
- **1 point**: Mentions the reduced effect on the overall efficiency of the electron transport chain.

b. Zou een niet werkend Complex I de gehele ATP-productie stopzetten? Waarom wel/niet?

- **2 points**: Explains that **ATP production might continue** because electrons can still enter through Complex II.
- **Or 1 point**: describes only *alternative complexes or* entry points for electrons.

Question 3: Proton Gradient and ATP Synthesis (Total: 8 points)

a. Hoe wordt dit protongradiënt opgebouwd?

- **1 point**: Identifies Complex I.
- **1 point**: Identifies Complex III.
- **1 point**: Identifies Complex IV.
- **1 point**: Describes the creation of a high concentration of protons through pumping in the intermembrane space.

b. Hoe wordt dit protongradiënt gebruikt door de sub-eenheden van ATP-synthase om ATP te produceren?

- **1 point**: Describes proton flow back into the mitochondrial matrix.
- **1 point**: Mentions rotation of F0 subunit.
- **1 point**: Mentions conformational changes in F1 subunit.
- **1 point**: Explains how conformational changes enable the binding of ADP and inorganic phosphate to produce ATP.

Question 4: Role of Electron Transport Molecules (Total: 5 points)

a. Tussen welke complexen transporteert Co-enzym Q elektronen?

- **1 point**: identifies 1-3
- **1 point**: identifies 2-3

b. Hoe zou de ATP-productie worden beïnvloed als Co-enzym Q geen elektronen meer kan transporteren?

- **1 points**: Describes how electron flow through the chain would halt,
- **1 point**: Mentions that this disruption would stop proton pumping
- **1 point**: No energy for ATP production.
- **alternatively**: describes that Complex I still pumps protons and ATP production is reduced (**2 points).**

Question 5: Role of Oxygen and Consequences of Its Absence (Total: 8 points)

a. Wat gebeurt er bij het eindstation van de elektronen transport keten en waarom is zuurstof nodig?

- **1 point**: identifies oxygen necessary for taking up electrons
- **1 point**: identifies oxygen needed to form water

b. Wat zou er gebeuren met het elektronen transport als er geen zuurstof aanwezig is in de cel?

- **1 point**: Describes that electrons cannot move/get stuck
- **1 point**: Describes that this prevents pumping of protons and the creation of a proton gradient
- **1 point**: Describes that ATP production stops
- **alternatively**: describes that Complex I still pumps protons and ATP production is reduced (**2 points).**
- **additionally:** describes that this might form harmful byproducts cell death (**1 point)**

Question 6: Roles of NADH and FADH2 in Electron Transport and Proton Gradient Formation (Total: 6 points)

a. Waar brengen NADH en FADH2 hun elektronen naartoe?

- **1 point**: Identifies that NADH donates electrons to Complex I.
- **1 point**: Identifies that FADH2 donates electrons to Complex II.

b. Beschrijf hoe deze moleculen in verschillende maten bijdragen aan het proton gradiënt.

- **1 point**: describes that complex I (NADH) directly pumps protons.
- **1 point**: describes that complex II (FADH2) does not directly pump protons.
- **1 point**: describes that more total protons are pumped because of electrons from NADH
- **Or 1 point**: describes that less protons are pumped because of FADH2
- **Additionally**: Describes the flow of electrons through complexes III and IV and?

General Guidelines for Awarding Points

- **Correctness**: Accurate description and identification of components and processes.
- **Completeness**: Inclusion of all relevant aspects and steps.
- **Clarity**: Clear and coherent explanation demonstrating understanding of spatial and temporal organization.
- **Detail**: Additional details showing deeper understanding, even if not essential for the core answer.

Considerations for Missing Components

- **Spelling and Terminology**: Minor spelling mistakes (e.g., FADH2 spelled incorrectly) should not result in point deductions if the answer demonstrates clear understanding.
- **Partial Credit**: Award partial points for partially correct answers that reflect partial understanding of the concept.

F. Exploratory analyses

Exploratory factor analysis factor loadings IDQ-IHS.

Factor Loadings	F1 (21.4%)	F2 (16.7%)	Uniqueness
IDQ_F2_1	0.563	0.365	0.540
IDQ_F5_2	0.857		0.259
IDQ_F2_3	0.569	0.383	0.520
IDQ_F2A_4_R	0.503	0.526	0.458
IDQ_F5_5	0.666		0.495
IDQ_F2_6_R	0.456		0.787
IDQ_F2_7_R	0.612	-0.335	0.523
IDQ_F2_8	0.418		0.800
IDQ_F2A_9			0.906
IDQ_F2_10		-0.320	0.864
IDQ_F2A_11		0.872	0.177
IDQ_F2_12_R	0.360		0.816
IDQ_F2_13		0.437	0.740
IDQ_F2A_14_R		0.318	0.891
IDQ_F2A_15_R		0.658	0.504

Note. 'Minimum residual' extraction method was used in combination with an 'oblimin' rotation