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# Science teachers' and students' metavisualization in scientific modeling

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## Abstract

This study investigated eight experienced science teachers' and eight senior high school students' metavisualization when they drew models to represent their concepts of carbon cycling. Qualitative data collection techniques including think-aloud tasks and follow-up retrospective interviews were employed. The purposes of the study included: (1) to propose a framework differentiating performance levels leading to metavisual competence; and (2) to identify students' metavisualization difficulties by comparing experienced teachers' and novice students' performances. Four aspects of metavisualization were investigated, including use of epistemic knowledge of visualization, demonstration of metacognition in visualization, use of judgment criteria, and use of metavisual strategies. Levels of progression from none or less to sufficient metavisual competence were proposed based on the participants' metavisualization performances. Three types of epistemic knowledge of visualization were identified, namely, a view of visualization as a learning or expression tool, a static view of representation and target, and a dynamic view between purposeful visualization and knowledge construction. Five types of metavisual strategies were also identified, namely, resourcing, focusing, inducting, deducing, and perfecting strategies. Comparison of the teachers' and students' metavisualization indicates that the experienced teachers demonstrated distinctive metacognition and metavisual strategies that helped them achieve the goal of fluent visualization. The findings provide insights into how to support individuals' development of metavisual competence for scientific modeling.

**KEYWORDS**
metavisual competence, metavisualization, novice-expert study, scientific modeling

## 1 | INTRODUCTION

Scientific modeling is a type of science practice which is also important in science education. Learning science through modeling requires students to generate, explain, use, and critique models to communicate their ideas, solve problems, and develop theories, which are all essential scientific practices. Moreover, during the practice of scientific modeling, students need to apply and integrate their knowledge and skills. Research has evidenced that engaging students in scientific modeling practices would facilitate learning outcomes at least in three aspects: integrated understanding of science concepts (Bamberger & Davis, 2013; Bergan-Roller et al., 2018; Markauskaite et al., 2020), scientific literacy such as using scientific models to explain phenomena (Baumfalk et al., 2019), and epistemic understanding of scientific models and modeling (Baek & Schwarz, 2015).

As the majority of the research has focused on investigating effective pedagogies to engage students in scientific modeling practices (e.g., Campbell et al., 2015), an equally important and fundamental issue remains, which is why some people are more able to fluently engage in the modeling practice, whereas others cannot. In other words, what are the important factors that influence scientific modeling performance (Bamberger & Davis, 2013) or modeling competence (Gogolin & Krüger, 2018)? Research has indicated two important factors. The first involves content knowledge. Research has found that novices often possess unorganized conceptual frameworks in modeling practices, resulting in difficulties in their modeling performances (Al-Balushi, 2009). It has been recognized that an organized conceptual framework, or integrated knowledge, is necessary for successful modeling performance. Second, representational competence (Kozma & Russell, 1997, 2005), or competence of visualization (Gilbert, 2005, 2008), has been proposed as also playing a role. Representational competence refers to a set of skills including the generation and use of a variety of representations to explain science phenomena. Competence of visualization refers to the ability to generate and use visual displays of information such as graphs or diagrams. Recent empirical research has provided evidence for the important role of representational or visualization competence in modeling practices, and started to propose and investigate the core representational competences needed for different topics of scientific modeling (e.g., Chang, 2018; Griffard, 2013; Halverson & Friedrichsen, 2013).

Theoretically it has been suggested that the core of representational or visualization competence involves metavisualization (diSessa, 2004; Gilbert, 2005, 2008). As suggested by Gilbert (2005), "[i]f visualization is an important aspect of—especially in the sciences, …—then not possessing, having failed to develop, metavisual competence will have serious consequences" (p. 18). Metavisual competence involves a range of knowledge and skills needed in the practice of metavisualization. The perspective of metavisualization stresses the meta-aspects in the visualization process including the employment of metacognition and epistemic knowledge of visualization (Gilbert, 2005, 2008). For example, achieving metavisualization of a chemical reaction or other chemical phenomena involves students in becoming aware of the scope, functions, and limitations of various models or representations in use so that they are able to decide on when to use which models, such as the ball-and-stick, space filling, orbital models, or other symbolic and visual representations, to attain a given purpose of a visualization or modeling task (Gilbert, 2008). Without such knowledge, students might construct or use a limited representation, thus failing to fulfill the purpose of the visualization task. The knowledge of the scope, functions, and limitations of models and representations is defined as epistemic knowledge of visualization. Metacognition is also involved in achieving metavisualization such as the judgment of how multiple representations may complement each other to attain the goal of visualization and how difficult it will be to acquire and make meaning of these representations (Gilbert, 2008).

Compared to the construct of metavisualization which highlights higher order levels or progressive goals of visualization performance that students need to attain, the construct of visualization has a focus on complex cognitive activities such as visual imagery and visual perception (Gilbert, 2005). Research on visualization and representational competence for science learning encompasses a full range of activities and practices involving constructing and using representations with a main focus on conceptual and cognitive aspects (e.g., Griffard, 2013; Halverson & Friedrichsen, 2013; Kozma & Russell, 2005; Pande & Chandrasekharan, 2017; Tsui & Treagust, 2013). The perspective of metavisualization suggests that it is also important to pay attention to the metacognitive and epistemic aspects of visualization. Moreover, while research on representational competence for science learning has indicated common student difficulties in visualization such as the difficulty of generating and transforming multiple representations to represent and understand science concepts and phenomena (Pande & Chandrasekharan, 2017), the notion of metavisualization indicates key aspects of addressing these difficulties. It suggests that students need to develop and employ their metacognition and epistemic knowledge of visualization for successful visualization. Separate studies have indicated the importance of metacognition (Bennett et al., 2020) and epistemic knowledge about models and modeling (Lazenby et al., 2020; Schwarz & White, 2005) for the whole process of model-based learning, such as building and using models to generate scientific explanations. Applying the notion of metavisualization allows the focus only on the visualization construction part, but with a more holistic lens inclusive of both metacognition and epistemology to investigate how the two play a role in supporting students' successful visualization.

This study synthesized perspectives of metavisualization to operationalize it into four salient aspects. These four aspects were used as lenses to investigate the participants' metavisualization with the aim of proposing an analytical framework that can be used in research to analyze individuals' metavisualization performances in certain scientific modeling situations. Specifically, the participants were science teachers and students with various backgrounds. The selection of the participants aimed to maximize possible various performances of metavisualization so that different levels of metavisual competence can be identified. The subject area focused on the carbon cycle since it is a core science topic indicated in the national curriculum standards (Ministry of Education, 2014, 2018). Also, research has indicated that deep understanding of this science concept involves fluent uses of representations to represent objects on various scales such as molecules, cells, and ecological scales (Markauskaite et al., 2020; Mohan et al., 2009; Zangori et al., 2017).

The results of the current study may contribute to research on model-based learning by revealing students' difficulties in constructing models in the science topic of carbon cycling, and by proposing essential aspects, learning strategies, and competencies needed for fluent and successful construction of scientific models, given that constructing models of systems and phenomena through the use of representations and visualizations is a major practice of science (Kozma & Russell, 2005; Osborne & Quinn, 2017) and can address the call for science instruction transforming from a traditional didactic approach to an inquiry-based, constructive learning experience (Fuhrmann et al., 2020). The identified epistemic views of visualization in this study specified and exemplified epistemic knowledge needed in the specific phase of model construction, providing insights into the role of epistemic knowledge about models and modeling in science learning (Lazenby et al., 2020; Schwarz & White, 2005).

The results may also advance understanding of metavisualization and its role in scientific modeling. The proposed framework for metavisual competence may be adapted in further quantitative or qualitative studies to assess individuals' metavisual competence. The comparison of the teachers and students provides insights into how to support students in developing learning strategies to promote their metavisual competence. For example, investigating how individuals may demonstrate sufficient metavisual competence may provide insights into how to support novices in attaining their metavisual competence. On the other hand, research also calls for examining and developing teachers' metavisual competence (Eilam, 2015; Ferreira et al., 2011). The variations of metavisualization performances demonstrated by the teachers may suggest areas for developing teachers' metavisual competence.

# 2 | BACKGROUND

## 2.1 | Visualization construction in scientific modeling

Scientific modeling is an important scientific practice that can also benefit learners of science by helping them develop their conceptual understanding of science, scientific literacy, and epistemic understanding of science (e.g., Baek & Schwarz, 2015; Baumfalk et al., 2019; Markauskaite et al., 2020). Scientific modeling involves a variety of practices, such as developing visualizations and representations, using them to generate model-based explanations, and developing understanding of natural phenomena (Baumfalk et al., 2019). While the majority of the research on model-based learning has addressed the important issue of supporting students' model-based reasoning and explanations (e.g., Baumfalk et al., 2019; Forbes et al., 2015; Zangori & Forbes, 2016; Zangori et al., 2017), relatively few studies have focused on an equally important practice of modeling: the process of visualization construction. Specifically, what difficulties may students confront during the process of developing visualizations and representations? What are the important factors that lead to successful visualization? Research into these issues would provide fundamental insights with regard to how to support students in successfully developing visualizations and representations during the modeling process.

Visualization construction involves complex cognitive activities such as visual imagery and visual perception (Gilbert, 2005). Cognitive perspectives from research on drawing construction may provide some insights. Van Meter and Firetto (2013) proposed a cognitive model of drawing construction. The cognitive process involved includes the selection, organization, and integration of information to form visual representations, and then externalizing these representations to produce a drawing on the page. As in the other studies (e.g., Fiorella & Mayer, 2016; Fiorella & Zhang, 2018), the cognitive model also recognizes the importance of prior knowledge since learners' prior knowledge may influence how they comprehend the drawing task and what has been selected and retrieved to form the visual representation. Moreover, the model emphasizes the role of metacognition and self-regulation in the process of drawing. For example, learners' attempts to draw may trigger the awareness that the content is not well understood. Then learners may need to self-regulate the process such as seeking clarification or reinspection of the information retrieved or obtained. This model specifies the cognitive processes of drawing construction and identifies important factors including prior knowledge and metacognition. However, it may be general and not specific to drawing construction in scientific modeling. For example, what kind of prior knowledge is commonly required during visualization construction of scientific modeling?

In comparison, the perspective of metavisualization is proposed in the specific context of scientific modeling with the focus on visualization construction. It synthesizes from both perspectives of metacognition and modeling practice, which may be able to provide a comprehensive framework for investigating the process of visualization construction in scientific modeling.

## 2.2 | Metavisualization and its four practices in science learning

Gilbert (2008) suggests that "a fluent performance in visualization has been requiring metavisualization and involving the ability to acquire, monitor, integrate, and extend, learning from representations" (Gilbert, 2008, pp. 5–6).

He suggested that "'metacognition in respect of visualization' be referred to as 'metavisualization'" (Gilbert, 2005, p. 15). Clearly attaining the status of metavisualization involves, but might not be limited to, the employment of metacognition. Gilbert also recognized epistemic knowledge needed for metavisualization in science. For example, he defines that "[a] person with metavisual capability in the area of science will have a range of knowledge and skills in respect of the specific conventions associated with the modes and sub-modes of representation used there, together with more general skills of visualization *per se*" (Gilbert, 2005, p. 18). He explicitly listed epistemic knowledge of visualization needed to attain metavisualization in science, including knowledge of the conventions, scope, and limitations of each representation, among the other types of cognition and metacognition that he specified (Gilbert, 2005, p. 21). This type of knowledge is referred to as epistemic knowledge in the model-based learning literature (e.g., Lazenby et al., 2020; Schwarz & White, 2005). This is evidence that Gilbert's framework of metavisualization also involves employment of epistemic knowledge of visualization. The epistemic aspect is described as a meta-level in the research on epistemology (Barzilai & Zohar, 2016).

By discussing the model of metacognition by Nelson and Narens (1994), Gilbert (2005) indicated three stages concerned with image processing, namely acquisition, retention, and retrieval. He further added a fourth stage to the development of metavisualization, in addition to employment of metacognition:

> In the development of metavisualization—what might helpfully be called the development of 'metavisual capability'—the learner becomes increasingly aware of *monitoring* what image is being learnt, of how to retain that image, and how to retrieve it. I suggest that a fourth stage might be added to this model: *amendment*, the production of a version of the stored image that is retrieved for a specific purpose. (Gilbert, 2005, pp. 16–17)

He explicated that in the amendment stage of metavisualization, individuals consciously revise visualization for particular purposes. This also corresponds to his definition of metavisualization as including the ability to extend learning from representations.

Gilbert and colleagues (Gilbert, 2008, 2010; Justi et al., 2009) have suggested several criteria for the attainment of the metavisual status, that is, metavisualization, including (1) understanding of the convention of representation, (2) the ability to translate between modes of representation, (3) the ability to construct representations based on a given purpose, and (4) the ability to use representations to make predictions, understand phenomena, or solve novel problems using a model-based approach. He also discussed two strategies underlying the development of metavisualization, namely "to develop the epistemological beliefs about the nature of knowledge used by students" and "to have an acceptable understanding of the concept of 'model' itself" (Gilbert, 2008, p. 18). The criteria and strategies in Gilbert's work stress the importance of epistemic knowledge of visualization or models, as well as metacognition, for the attainment of metavisualization in science.

Similarly, diSessa (2004) used the term *metarepresentational competence* (MRC) to refer to a higher level of representational competence that engages the problematic aspects of representation, such as design choices of creating representations, judgment of relative values of representations, and uncertainties during the use and interpretations of representations. He suggests that individuals with well-developed MRC should be good at creating, critiquing, and comparing representations in terms of how they do or do not work in certain circumstances or based on some purposes. Practically, MRC involves mindful construction, manipulation, and utilization of external representations (Eilam, 2015).

Locatelli et al. (2010) and Locatelli and Davidowitz (2021) focused on the related cognitive and metacognitive process to define metavisualization as a process related to visualization and metacognition. From the cognitive perspective, visualization is perceived as an internal representation created by an individual, which can be expressed as external images. Metacognition is demonstrated to regulate the process of visualization, and hence metavisualization is attained. Their model indicates the important role of metacognition in metavisualization.

Four essential practices that are important to the development of metavisualization can therefore be identified by synthesizing these theoretical perspectives, including employment of epistemic knowledge of visualization (diSessa, 2004; Gilbert, 2005, 2008; Justi et al., 2009), demonstration of metacognition in visualization (Gilbert, 2005; Locatelli & Davidowitz, 2021; Locatelli et al., 2010; Van Meter & Firetto, 2013), being able to critique the adequacy of a visualization (diSessa, 2004; diSessa & Sherin, 2000), and use of metavisual strategies to construct visualization (Eilam, 2015; Gilbert, 2005, 2008, 2010; Justi et al., 2009).

First, epistemic knowledge of visualization such as knowing the conventions, purposes, functions, and limitations of a certain visualization seems to be essential. Research suggests the important role of metamodeling knowledge (Schwarz & White, 2005) or epistemic knowledge of models and modeling (Lazenby et al., 2020) in the whole process of scientific modeling. Specifically, metamodeling knowledge refers to knowledge in four dimensions, namely, the nature of models, the process of modeling, the purpose or utility of models, and the evaluation of models (Schwarz & White, 2005). Lazenby et al. (2020) suggest five aspects of epistemic knowledge about models and modeling: model changeability, model multiplicity, evaluation of models, process of modeling, and nature of scientific inquiry. Epistemic knowledge of visualization in the context of scientific modeling should be a branch of metamodeling knowledge with a specific focus on knowledge of visualization. This study investigated how epistemic knowledge was mostly demonstrated as the participants developed their visualizations, focusing on the specific phase of visualization during the modeling process. The perspectives of metavisualization (Gilbert, 2005, 2008; Justi et al., 2009) and MRC (diSessa, 2004) have also stressed the importance of the epistemic aspects in the attainment of metavisualization as has been discussed in the foregoing paragraphs.

Another essential practice of metavisualization involves metacognition, which is referred to as metacognition in the specific context of visualization (Gilbert, 2005). In general, metacognition includes knowledge of cognition and regulation of cognition; the former is also referred to as metacognitive knowledge and the latter as metacognitive skills (Brown et al., 1983). How metacognition is demonstrated and plays a role in the modeling process of visualization construction is investigated in the study.

Being able to critique the adequacy of a visualization can be related to model evaluation which is an important practice of scientific modeling (Lazenby et al., 2020; Schwarz et al., 2009). It may refer to evaluation of a peer's model, an alternative model or a consensus model. Even in the early phase of developing personal visualizations and models, the ability to critique one's own or other's visualization to find the problematic aspects of visualization for improvement is important in producing quality visualizations, and comprises a major part of MRC (diSessa, 2004; diSessa & Sherin, 2000). The practice of critiquing visualization may involve extensive use of epistemic knowledge that has also been stressed in the framework of metavisualization by Gilbert (2005, 2008). Also, the amendment stage of metavisualization including revisions of visualizations by Gilbert (2005) is related to the practice of critiquing visualizations.

Finally, the literature suggests the use of metavisual strategies to achieve fluent and successful visualization (Eilam, 2015; Gilbert, 2005, 2008, 2010; Justi et al., 2009). Metavisual strategies can be defined as a systematic series of planned actions by the employment of knowledge and skills for achieving a particular goal of visualization during scientific modeling (Hung et al., 2021). Research has recognized the importance of teaching metavisual strategies to enhance instruction with visualizations (Locatelli & Arroio, 2014, 2015, 2016). While these studies focused on a specific type of metavisual strategy, this study investigated the variety of metavisual strategies demonstrated by the participants, which may be made available for future teacher professional development or learning interventions.

## 2.3 | Metavisual competence

Individuals may demonstrate differently in the four practices of metavisualization, thus showing variations in performance levels from none or less to sufficient metavisual competences. Gilbert (2005) indicates that metavisual competence refers to a type of advanced competence that can be differentiated from competence of visualization which refers to a fundamental type of competence. Similarly, diSessa's (2004) proposal of MRC recognizes the need to distinguish between representational and MRC.

Gilbert (2008) indicates that "[a]cquiring metavisual status implies being able to progressively acquire understanding of (i.e., being able to visualize) representations at the 3D, 2D, 1D, level and being able to move between them" (p. 19). He then exemplified his point by discussing the scheme of "progression in representational competence" by Kozma and Russell (2005) who differentiated representational competence in chemistry into five levels, from "Level 1 Representation as Depiction" to "Level 5 Reflective, Rhetorical Use of Representations." Level 1 specifies the performance that only generates representations based on physical features, whereas Level 5 indicates the performance that students can take "the epistemological position" to construct and use representations and explain why some representations are more appropriate than others (Kozma & Russell, 2005). This discussion indicates the progressive nature of representational competence which may progress from non- or less-metavisual to metavisual competences. The benefit of proposing and using the construct of metavisual competence is that it helps underscore the necessity of focusing on the meta-aspects including metacognition and epistemology for achieving higher levels of visualization performances in science.

Locatelli and Arroio (2015) searched for research articles that mentioned "metavisual" in the field of science education from 2008 to 2014 and found only 17 articles, 70% of which were empirical studies and most of which focused on analyzing students' performances. No science education article mentioned "metavisual" before 2008. The results of the review by Locatelli and Arroio (2015) indicate that the focus on metavisual competence for science learning is starting to gain attention. However, the majority of the studies applied theoretical perspectives based on multiple representations (e.g., Chittleborough & Treagust, 2008) or scientific modeling (e.g., Wang & Barrow, 2011) but found the importance of metavisual competence or metavisual strategy in their study. Probably due to the limited scope or focus of an article, these studies did not further discuss the metavisual constructs, leaving areas for future research. On the other hand, research on promoting teachers' metavisual competence is also starting (e.g., Eilam, 2015; Ferreira et al., 2011). Based on the perspective of pedagogical content knowledge, Melo-Niño et al. (2017) suggested that teachers need visual pedagogical content knowledge. These studies indicate the important role of metavisual competence in science education. More studies are needed to investigate how to develop science teachers' and students' metavisual competence.

As fundamental steps for developing teachers' and students' metavisual competence, the current study investigated the variations among the participants, including teaching experts and novice learners, with the aim of proposing a framework of progressive levels leading to metavisual competence. Previous literature has indicated the important role of content knowledge in scientific modeling. Therefore, theoretically experienced science teachers would demonstrate better metavisual competence than novice learners since they have established content knowledge. The comparison of science teachers and students in this study may provide empirical evidence for or against this claim. Also, the in-depth analysis of different practices of metavisualization among the participants may indicate how experienced experts may differ from novice learners in metavisualization. The results of this study would help provide insights into analytical methods for metavisual competence, and into strategies and approaches to facilitate novices' development of metavisual competence, which is believed to be a core of successful scientific modeling performance (diSessa, 2004; Gilbert, 2005, 2008, 2010), but little empirical research has addressed this aspect.

## 2.4 | Modeling carbon cycling

Common student difficulties in modeling carbon cycling include a lack of integrated content knowledge such as understanding key carbon cycle processes including photosynthesis and cellular respiration, and the difficulty of visualizing carbon cycling on a global scale (Zangori et al., 2017). Indeed, modeling carbon cycling requires the application of knowledge and skills to generate multiple representations to express ideas, make predictions, and solve problems. Specifically, it requires an understanding of science concepts including the forms, reactions, and interactions of carbon elements in the atmosphere, the biosphere, the hydrosphere, and the lithosphere (Markauskaite et al., 2020), and the employment of skills to represent the parts, processes, and relationships of the carbon cycle to form a model (Bergan-Roller et al., 2018). Also, such modeling tasks require the use of multiple representations with different modes and levels. Modes of representation refer to the use of different forms such as drawings, diagrams, graphs, tables, or equations to represent science concepts or phenomena with different degrees of abstractness (Tsui & Treagust, 2013). Levels of representation refer to external representations on different scales or from different perspectives; for example, in biology, the macroscopic level represents biological structures visible to the naked eye, the microscopic level represents structures visible under a microscope, and the molecular or symbolic level represents DNA or chemicals (Tsui & Treagust, 2013).

Effective model-based learning activities have been developed and implemented to foster students' model-based reasoning and explanations on the topic of carbon cycling (Zangori et al., 2017) or to help students develop understanding of carbon cycling connected to climate change (McNeill & Vaughn, 2012). While these studies focused on the important aspect of providing support to improve student learning and understanding through the verbal and textual approach, this study addressed the issue of how to promote model-based learning with a focus on the visualization that students create. The metavisualization perspective was applied as a lens to help reveal variations in participants' performances of visualizing carbon cycling. The findings would provide insights into ways to guide students' generation of quality visualization in scientific modeling.

# 3 | METHODS

## 3.1 | Participants and context

Eight experienced science teachers and eight senior high school students in Taiwan participated in the study. The recruitment and selection of the participants aimed to be able to provide information with regard to various performances of metavisualization considering their background in science and science education. They were based on purposeful sampling. The eight science teachers consisted of four college science teachers (CST1–CST4) and four high school science teachers (SST1–SST4). The college teachers were recruited and selected for their comparable backgrounds, since they had all obtained PhDs specializing in biological- and environmental-related science. Each of them was from a different public, research-based university in Taiwan, and their primary responsibilities as faculty members included both teaching and researching. The college teachers were therefore also scientists. The other four high school science teachers came from different public high schools in Taiwan and were also recruited and selected for their comparable backgrounds. All of them had majored in biology. They were PhDs or PhD candidates in science education, but their primary responsibility at their schools was teaching. They had been teaching in high schools for more than a decade.

The eight high school students consisted of four Grade-12 students (CS01–CS04) and four Grade-10 students (CS11–CS14) recruited at one public senior high school with consideration of their backgrounds in science learning and their averaged school science achievements. All of the students agreed to participate with no extra credit for their school grades. The students had learned the basic knowledge related to carbon cycling in Grade 7 (from the perspective of biology) and Grade 9 (from the perspective of geology). The Grade-12 students had attended more elective science courses than the Grade-10 students. All of the students demonstrated medium achievements in school science, meaning that they were not particularly high- or low-achieving students. According to the science teachers at the school, the instruction of the science courses involved mainly textbook-based, teacher-centered lectures, with little emphasis on modeling or visualization practice.

## 3.2 | Procedures and interview questions

The interview consisted of think-aloud tasks and follow-up retrospective interview questions to investigate the participants' metavisualization while conducting a scientific modeling task. Two graduate students, one in a PhD program and the other in a Master's program, were trained to be the interviewers following the detailed interview protocol. The modeling task in the interview focused on the topic of carbon cycling in the Earth's system among the four spheres, since the topic involves complex phenomena that require modeling and visualization on multiple scales (Lazarowitz & Penso, 1992; Mohan et al., 2009). Moreover, for all of the participants including the teachers and students, creating a model of carbon cycling among the four spheres of the Earth goes beyond simply reproducing a standard disciplinary model since it requires content knowledge in both biology and geology. No figures or diagrams in the textbooks have represented carbon cycling among the four spheres in one model.

The participants were asked to make drawings (i.e., their models) using a mobile application named DrawScience (Chang, 2018) to construct their models of carbon cycling and to think-aloud to describe their process of modeling. DrawScience was used since it allows users to make drawings and animations for science topics efficiently with easy-to-use functions and objects (Chang, 2018). Users can create any form of visualization such as diagrams, concept maps, pictures, or free-form drawings.

The interview tasks and questions were developed and underwent several rounds of revision by two science educators and one science teacher. An analysis of how the tasks and questions provided data for investigation of the four aspects of metavisualization is summarized in Table 1. Before the main visualization task and retrospective interview, the participants were asked to carry out one practice activity to familiarize themselves with the think-aloud process and the use of DrawScience. After the practice activity, the main visualization task asked the participants to "draw a picture to represent the transformation process and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere." After the drawing task, the participants were asked to critique a visualization given by the interviewer, which was drawn by an individual who was not a participant in this study. The question asked: "This is a drawing of transformation processes and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere. Does this drawing need to be revised? Please revise this drawing and explain your revision if necessary."

There were 10 follow-up retrospective questions after the drawing and critiquing tasks, including four aspects: reflection on the criteria of critiquing visualization, such as "What were the criteria that you used to judge whether to revise that picture or not?"; reflection on the resources, such as "What is hard for you when performing these tasks?" and "What resources do you need while performing these visualization tasks?"; understanding of the nature of visualization purposes and limitations, such as "What are the functions, advantages, and limitations of your drawing?" and "What characteristics do you think a good visual representation should have?"; and reflection on the strategies used for visualization, such as "What strategies would you suggest if a middle school student wanted to draw a picture of carbon cycling?" The task and interview were carried out without a time limit. On average, it took about 30–40 min for a participant to complete the task and interview. The interviews were videotaped and transcribed. A computer with Internet access was provided for the participants to use during the visualization tasks to search for the information needed, but only textual information was allowed.

## 3.3 | Data analysis

The interviews were transcribed. NVivo was used to aid the coding and analysis processes. An original coding framework based on one case teacher by Hung et al. (2021) was used and revised using the data from the 16 participants in this study. The coding framework was generated considering both the literature and data (Table 2). For example, the metavisualization literature suggests focusing on content knowledge, metacognitive knowledge, metacognitive skills, epistemic knowledge of visualization, and metavisual strategy. The subcategories of these five categories were then

**TABLE 1** Item analysis of the interview tasks and questions by the four aspects of metavisualization

| Aspect | Think-aloud task | Retrospective question |
|---|---|---|
| Demonstrate epistemic knowledge of visualization | "Draw a picture to represent the transformation process and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere" | "What are the functions, advantages, and limitations of your drawing?" |
| | "This is a drawing of transformation processes and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere. Does this drawing need to be revised? Please revise this drawing and explain your revision if necessary" | "What characteristics do you think a good visual representation should have?" |
| Demonstrate metacognition during visualization | "Draw a picture to represent the transformation process and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere" | "What is hard for you when performing these tasks?" |
| | "This is a drawing of transformation processes and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere. Does this drawing need to be revised? Please revise this drawing and explain your revision if necessary" | "What resources do you need while performing these visualization tasks?" |
| Critique the adequacy of a visualization | "Draw a picture to represent the transformation process and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere" | "What were the criteria that you used to judge whether to revise that picture or not?" |
| | "This is a drawing of the transformation processes and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere. Does this drawing need to be revised? Please revise this drawing and explain your revision if necessary" | |
| Use metavisual strategies to achieve visualization tasks (construct and critique visualization) | "Draw a picture to represent the transformation process and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere" | "What strategies would you suggest if a middle school student wanted to draw a picture of carbon cycling?" |
| | "This is a drawing of transformation processes and the formation of the carbon compounds among the hydrosphere, biosphere, geosphere, and atmosphere. Does this drawing need to be revised? Please revise this drawing and explain your revision if necessary" | |

**TABLE 2** Summary of coding of metavisualization in scientific modeling of carbon cycling

| Category | Definition/description |
|---|---|
| Content knowledge (CK) | Scientific knowledge and understanding of carbon cycling demonstrated during modeling |
| Formation of carbon compounds | Response indicated that the carbon atom forms numerous compounds and exists in nature |
| Carbon compounds existing in the earth's different spheres | Response indicated that carbon compounds transformed in two or more of the earth's spheres |
| Reactions and interactions | Response indicated the chemical and physical reactions and interactions between the components of ecosystems regarding carbon cycling |
| Metacognitive knowledge (McK) | The knowing about one's cognition |
| Awareness of one's own inadequacies | Response indicated awareness of the inadequacies and deficiency of his/her own conceptions or visualizations |
| Awareness of one's own strengths | Response indicated awareness of the conditions and resources to strengthen the performance of the visualization task |
| Metacognitive skills (McS) | Use of metacognitive knowledge to conduct metacognitive regulation |
| Planning | Response indicated planning of the steps to complete the visualization task |
| Monitoring | Response indicated monitoring of the execution progress in the visualization task |
| Reflecting | Response indicated reflection on the visualization to make sure ideas were expressed clearly and the accomplished task met the purpose |
| Epistemic knowledge of visualization (EpK) | The epistemological aspect of visualization knowledge |
| Knowledge of the purposes or functions of the visualization | Response indicated knowledge and understanding of functions, advantages, and purpose of the visualization |
| Knowledge of the limitations of the visualization | Response indicated knowledge and understanding of limitations and disadvantages of the visualization |
| Knowledge of visualization strategies | Response indicated explicit awareness and knowledge of the strategy that can help conduct visualization tasks |
| Judgment criteria of the visualization | Criteria used by the participant for evaluating the quality of the visualization |
| Metavisual strategy (MvS) | Systematic series of planned actions for achieving a particular goal of visualization |
| Resourcing strategy | Response indicated that the participant retrieved existing conceptions to comprehend the task or based on the purpose of the task, and identified resources for the enhancement of conception retrieval |
| Focusing strategy | Response indicated that the participant monitored progress by continuously matching among their own conceptual framework, the expressed visualization, and the goal of the task |
| Inducting strategy | Response indicated that the participant used reflection to identify concepts needed in the task, and gained or organized the concepts to guide their action for the visualization task |

**TABLE 2** (Continued)

| Category | Definition/description |
|---|---|
| Deducing strategy | Response indicated that the participant applied their own conceptual framework or knowledge to guide the action for the visualization task |
| Perfecting strategy | Response indicated that the participant interactively implemented conceptual knowledge and epistemic knowledge and metacognitive skills to achieve a high quality of visualization |

generated based on the analysis of the data. For example, for the category of epistemic knowledge of visualization, the participants' demonstration of this type of knowledge could be further categorized into four subcategories, including knowledge of the purposes or functions of the visualization, knowledge of the limitations of the visualization, knowledge of visualization strategies, and knowledge of judgment criteria of the visualization.

The refinement of the framework was achieved during the coding process in multiple iterations of coding and discussion among the author and two independent coders. One same case was coded in each iteration. Every inconsistent code was discussed until a consensus was reached by modifying or detailing the framework. A summary of the coding categories and their definitions is provided in Table 2. Eight of the 16 participants were coded by the two independent coders. The percentage agreement of the coding reached 74%. Inconsistent codes were further discussed and resolved. They then proceeded to code the rest of the data. Moreover, the proposal and coding of the levels progressing to metavisual competence were achieved by iteratively reviewing the codes and transcripts and validating by searching for confirming and disconfirming evidence from the data.

## 4 | FINDINGS

### 4.1 | Overview of the metavisualization performances

Table 3 provides an overview of the participants' metavisualization performances. It was observed that the major differences of the performances were shown between the teachers and students, but not between the subgroups of each (e.g., college and high school teachers, or 10th- and 12th-grade students). Overall, the content knowledge of how carbon compounds exist in the earth's different spheres, and how the carbon element and compounds react and interact within and across the spheres is necessary for the visualization task since all participants applied the content knowledge. The participants also demonstrated awareness of their own strengths and inadequacies during the visualization task.

Comparing the teachers' and students' performances, it was found that more teachers showed the following aspects: knowledge of the limitations of the visualization, knowledge of visualization strategies, monitoring, reflecting, and using metavisual strategies. On the other hand, more students demonstrated planning. The majority of the science teachers were familiar with the topic, at least the biosphere part of carbon cycling, since they all teach biology. It was observed that three of them did not plan their actions during the visualization tasks, whereas only two of the eight students did not conduct planning. Overall, more teachers demonstrated metavisualization, including demonstration of metacognitive knowledge, metacognitive skills, epistemic knowledge of visualization, and metavisual strategies.

### 4.2 | Proposal of performance levels progressing to metavisual competence

The following analysis specifically focuses on the four salient aspects of metavisualization practices, namely, applying epistemic knowledge of visualization, demonstrating metacognition during visualization, using

**TABLE 3** Numbers of the participants' performance demonstrated in each category of metavisualization

| Category | $N_{Teacher}$ | $N_{Student}$ |
|---|---|---|
| Content knowledge (CK) | | |
| Formation of carbon compounds | 5 | 5 |
| Carbon compounds existing in the earth's different spheres | 8 | 8 |
| Reactions and interactions | 8 | 8 |
| Metacognitive knowledge (McK) | | |
| Awareness of one's own inadequacies | 8 | 8 |
| Awareness of one's own strengths | 8 | 8 |
| Metacognitive skills (McS) | | |
| Planning | 5 | 6 |
| Monitoring | 6 | 2 |
| Reflecting | 5 | 2 |
| Epistemic knowledge of visualization (EpK) | | |
| Knowledge of the purposes or functions of the visualization | 8 | 8 |
| Knowledge of the limitations of the visualization | 7 | 0 |
| Knowledge of visualization strategies | 8 | 7 |
| Judgment criteria of the visualization | 8 | 8 |
| Metavisual strategy (MvS) | | |
| Resourcing strategy | 2 | 2 |
| Focusing strategy | 7 | 2 |
| Inducting strategy | 2 | 1 |
| Deducing strategy | 8 | 6 |
| Perfecting strategy | 1 | 1 |

judgment criteria to critique visualizations, and using metavisual strategies to facilitate processes of visualization, which were the categories also synthesized from the literature.

The current study, based on the analysis of the various responses and performances provided by the 16 participants, further proposes different levels in each aspect to comprise the metavisual competence framework which indicates various levels progressing to metavisual competence (Table 4). Level 0 in each aspect is defined as no demonstration of the knowledge or performance in that aspect. For example, some participants might not demonstrate any epistemic knowledge of visualization during the visualization task, and were unable to specify their understanding regarding the nature, functions or limitations of visualization during the retrospective interview. Therefore, this kind of performance was defined as Level 0 in the aspect of applying epistemic knowledge of visualization. The rest of the levels (i.e., Levels 1, 2, and 3) are defined and evidenced as follows. It needs to be noted that a Level 3 performance indicates demonstration of sufficient metavisual competence in an aspect, whereas Level 0, 1, or 2 performances indicate demonstration of non- or less-metavisual competence.

**TABLE 4** Metavisual competence aspects and levels of progression from non- or less-metavisual to metavisual competence

| Aspect | Level 0 | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| Demonstrate epistemic knowledge of visualization | Did not develop epistemic knowledge of visualization;<br>Was not able to think of a function or limitation of visualization per se. | Indicated functions of visualization as facilitating learning, helping memory, expressing ideas in a comprehensible way or a way different from using text;<br>Was not able to think of a limitation of visualization per se (a view of visualization as a learning or expression tool). | Indicated functions of visualization to simplify phenomena or ideas, to make the abstract concrete, to present a whole structure;<br>Indicated visualization as not an exact copy of the target, details of the target may be missing in a representation (a static view of representation and target). | Knew functions of visualization to help reconstruct knowledge;<br>Knew conventions of multiple representations (text, symbols, graphs) complementary to each other to form a visualization based on a purpose, misinterpretation occurred when purposes and conventions mismatched between makers and readers (a dynamic view between purposeful visualization and knowledge construction). |
| Demonstrate metacognition during visualization | Did not demonstrate metacognition during visualization. | Was aware of his/her difficulties and strengths in making a visualization. | Was aware of his/her difficulties and strengths in making a visualization;<br>Regulated the visualization process by planning. | Was aware of his/her difficulties and strengths in making a visualization;<br>Regulated the visualization process by monitoring or reflecting. |
| Critique the adequacy of a visualization | Was not able to critique the adequacy of a visualization. | Critiqued a visualization based on personal preference for the appearance (a personal view). | Critiqued a visualization based on the judgment criteria of adequate content represented (conciseness, correctness, or completeness) (a static view of representation and target). | Critiqued a visualization considering a set of judgment criteria including adequate content and considering readers and purposes (a dynamic view of visualization and communication). |
| Use metavisual strategies to achieve visualization tasks (construct and critique visualization) | Did not use any metavisual strategies. | Used primary strategies, the recall or imitation strategy to aid the process of visualization. | Used satisfactory metavisual strategies, including resourcing or deducing strategies that help engage in mindful cognition. | Used metavisual strategies including focusing, inducting, or perfecting strategies that make use of high levels of epistemic knowledge and metacognition |

### 4.2.1 | Demonstration of epistemic knowledge of visualization

Differences in the demonstration of epistemic knowledge of visualization was observed. A relatively basic performance is defined as Level 1 in that the respondent was able to indicate the function of visualization so as to facilitate learning or help memory or personal expression, but was not able to think of a limitation of visualization per se. For example, when asked about the functions and advantages of the visualization that the student drew or a visualization provided in textbooks, common student responses included the following.

> CS03: Unlike textbooks which are always describing and describing, I think this kind (of drawing/visualization) would be helpful and make my learning more efficient.

> CS04: I can express [myself] through drawing…using drawing to replace textual expression.

Overall responses at this level viewed the function of a visualization as a learning or expression tool. When asked about the limitations of a visualization, the majority of the high school students had difficulty comprehending what the interviewer meant regarding the limitation of a drawing or visualization. Many of them comprehended this question as asking about their difficulties during visualization or drawbacks of their own visualizations, and responded with comments such as “My drawing is not that beautiful” (CS02), “I haven't entirely set up all the details of my drawing” (CS04), or “My drawing is not that imaginative” (CS12). Despite the attempt to clarify the meaning of the interview question by the interviewer, most of the high school students were not able to reflect on the limitations of a visualization per se.

A Level 2 response indicates the understanding of visualization in light of the relationship between a representation and its target in the two aspects of both functions and limitations. The following excerpt exemplifies this.

> CST1: Pictures or drawings can make complex statements simple….However, they are limited because a lot of details cannot be represented in the picture.

The majority of the teachers demonstrated Level 2 epistemic knowledge of visualization. Moreover, some of them further indicated the relationships between not only the representation and its target, but also representation constructing and knowledge reconstructing, which was categorized as a Level 3 response.

> CST2: The function of a picture or drawing is not just that it helps solve problems, it's also…during the process of making drawing, it's actually restructuring your concepts and ideas.

> CST2: Sometimes I feel that using some visual representations in drawings is not as fluent as when you directly explain a picture or a concept….Sometimes some drawings do not achieve their goals….For example, actually a reader may need to think a lot…when you draw without explanation you leave readers to make their own interpretations…sometimes drawing alone cannot convey some ideas.

The excerpts show that CST2 demonstrated a dynamic perspective that during the visualization process not only are representations made, but knowledge is reconstructed. Also, his view of a limitation of a visualization is dynamic because it depends on how the maker conveys ideas based on adequate representations considering their conventions and purposes, and on how the reader interprets the representations. It was found that three of the eight science teachers demonstrated Level 3 epistemic knowledge of visualization.

### 4.2.2 | Demonstration of metacognition during visualization

All of the participants, including the teachers and students, were aware of their own difficulties and strengths during the visualization process. Therefore, it is defined that such awareness indicates a basic level (i.e., Level 1) of demonstrating metacognition in visualization. It was observed that what made a difference between a lower and higher level of metacognition depended on how well the participants regulated their progress of visualization using metacognitive skills including planning, monitoring, or reflecting. However, it was also observed that when the participants were familiar with the content area (i.e., carbon cycling in this case), explicit planning of visualization before starting drawing might not be necessary. Rather, all of the experts (science teachers) constantly employed monitoring or reflecting during visualization, whereas only two novices did so. As a result, it is defined that a Level 2 performance includes awareness of one's own strengths and limitations, and the employment of planning before the task. On top of that, a Level 3 performance demonstrates metacognitive regulation including monitoring or reflecting. Some of the participants performed planning before they started:

> CS14: I will draw two parts. For the first part I will draw the forms of carbon in nature. I will draw first and then use text to explain. (planning)

The following two excerpts show an example of monitoring and reflecting, respectively, as two aspects of metacognitive regulation.

> SST1: What's in the ocean? Carbon elements in the ocean…(typing)…OK, I know the composition of the ocean. Then it involves water cycling. Yes, like evaporation, condensation and precipitation… wait, no, let me check my drawing. Let me check the question. (monitoring)

> CS02: In the hydrosphere…I think of calcium carbonate. Yes, it is a form including carbon elements. And then in the lithosphere…is it [calcium carbonate] in the lithosphere? Or in the hydrosphere? … What am I missing? Am I making it correct [in terms of conceptual accuracy]? (reflecting)

While planning may help participants get started, monitoring may help them make sure their progress of visualizing is in the right direction to achieve the goal of visualization, and reflecting may help them identify the places in the visualization or in their knowledge framework that are questionable and need improvement.

### 4.2.3 | Use of judgment criteria

When asked to critique the adequacy of a visualization, the participants' performances were categorized into different levels. The lowest level (Level 0) refers to the inability or reluctance to critique a given visualization, such as responding, "It looks great!" without analyzing the details of the presented visualization (CS02). A Level 1 response involves the performance by the participant who critiqued the visualization based on personal preference for the appearance, which employed only personal views, such as "the grass drawn here looks too big" (CS13). A Level 2 response employs judgment criteria including conciseness, correctness, or completeness to critique the given visualization. The following excerpt exemplifies this level of response which critiqued the given visualization based on completeness.

> CS04: Well…this picture only shows the exchange between the ocean and land. It shows the exchanges among the hydrosphere, lithosphere, and biosphere. I would add the atmosphere here. (Completeness)

On top of considering the conciseness, correctness, or completeness of the visualization, some participants demonstrated a response that also considers the purpose of the visualization and its potential readers.

> SST3: First, I would think that the presentation of this drawing did not show the process of "cycling" (given that the question asks to draw carbon cycling). Compared to what I drew, I intended to show "cycling," but here this drawing only shows one-way lines.

SST3's response was triangulated by the retrospective interview data. When asked, "What are the criteria that you used to judge whether to revise that picture or not?" and "What characteristics do you think a good visual representation should have?", SST3 responded "I revised to make it more complete…also I need to see what the purpose is. If the purpose is to show carbon cycling…then revising it to show all the paths would be more complete," and "A good picture…sometimes I might not agree with the presentation of the pictures in the textbooks. When I disagree, it doesn't mean that it is wrong. It's just that I don't think the presentation or structure is good enough for student learning." Since this kind of response considers not only the relationship between representation and target, but also a dynamic view regarding the purpose of visualization and its readers, a further level (Level 3) was generated for this kind of performance.

### 4.2.4 | Use of metavisual strategies

In the previous study (Hung et al., 2021), five types of metavisual strategies were identified based on data from one case teacher. The current study revised the types and definitions of the metavisual strategies using the data from 16 participants. The five types of metavisual strategies were re-examined and redefined in the study, namely (1) the resourcing strategy, meaning retrieving existing conceptions to comprehend the task or based on the purpose of the task, and identifying resources for the enhancement of conception retrieval, (2) the focusing strategy, meaning monitoring progress by continuously matching among one's own conceptual framework, the expressed visualization, and the goal of the task, (3) the inducting strategy, meaning using reflection to identify concepts needed in the task, and gaining or organizing the concepts to guide the action for the modeling task, (4) the deducing strategy, meaning applying one's own conceptual framework or knowledge to guide the action for the modeling task, and (5) the perfecting strategy, meaning interactively implementing conceptual knowledge and epistemic knowledge of visualization with metacognitive skills to achieve a high quality of visualization. Two additional types of action were identified which were mainly from some of the students' performances: (6) intuitive drawing or modeling where no specific strategies were observed or elaborated, and (7) recall strategies whereby participants tried to recall diagrams or visualizations seen before for making their own visualizations. The last two are not metavisual strategies since no metacognition or epistemic knowledge of visualization was observed in the action.

The participants' performances in the use of metavisual strategies could be differentiated into four levels (Table 4). Level 0 means that no metavisual strategies were employed or elaborated, such as with intuitive drawing. The following excerpt shows an example.

> CS04 (making the drawing shown in Figure 1): The carbon element is in the hydrosphere. It is carbon dioxide dissolved in the water, so they will be in the hydrosphere, in the water. There is a lot of carbon dioxide in the air, so in the atmosphere. Then in the rock, it is more like carbon itself, like coal, so this is in the lithosphere. In the biosphere carbon exists in many places in our body, so it is in the biosphere. The plant absorbs carbon dioxide. It will become carbon in the plant. Then after living things die, part of it will become rocks in the lithosphere. There are more exchanges in the hydrosphere and atmosphere. The coal in the rock is dug out and burned and then it will go into the atmosphere.

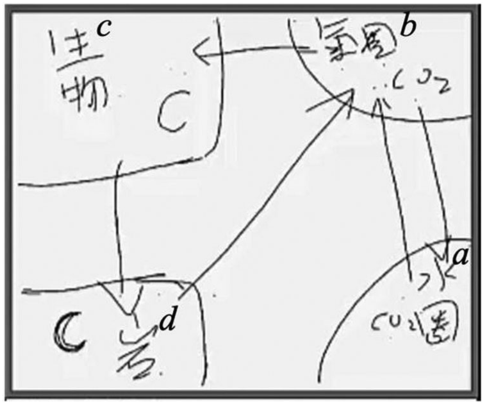


**FIGURE 1** CS04's drawing of carbon cycling. Translation made for this manuscript: a, hydrosphere; b, atmosphere; c, living things; d, rock

CS04 did not employ too much cognitive or metacognitive effort. His drawing mainly iterated what was stated in the question without further details or reasoning, that is, carbon elements and their interactions in the earth's spheres.

A Level 1 performance is defined as participants using the recall or imitation strategy to aid the process of visualization. This strategy was identified only in the retrospective interview; when asked to suggest a good drawing strategy, about half of the eight students indicated that a good strategy of modeling carbon cycling would be to imitate or reference existing diagrams, such as “It's just that you can look at how other people make the drawing” (CS01), or “Look at the textbook, then draw it by yourself” (CS13). Note that imitation does not necessarily mean copying since some of them also emphasized, “You need to comprehend; don't just copy the diagram” (CS11), or “You can imitate, but you also need to add what you want to express” (CS14). However, in the actual visualization process no participants demonstrated this level of performance since they were not allowed to look at any other diagrams or drawings during their process of drawing, but some of them tried to recall what they had seen in the textbooks as some of the students’ drawings bore a resemblance, to some degree, to a model in the textbook.

Another higher level of performance, Level 2, was observed. Participants demonstrating such performance exerted a fair amount of cognitive effort to retrieve knowledge or to search for resources needed for their visualizations. In this case, metacognition needs to be employed but may be implicit since participants have to judge what kinds of knowledge or resources are needed; however, the judgment may be executed automatically or it is difficult to articulate. Some of the participants used the resourcing strategy, exemplified by the following excerpt.

> CS14: Carbon cycling, the hydrosphere, biosphere, geosphere, and atmosphere…the hydrosphere should mean the ocean. I need to use the Internet to look up “carbon cycling” (searched the Internet and read the text). The changes in each sphere…carbohydrates decompose and become carbon dioxide and enter into the air. So, the carbon element comes from dead animals, animals eaten by other animals, and can be absorbed by plants. The factory or industry uses fuels, which causes emission of carbon dioxide. Now I am going to draw the sources in which carbon elements exist.

Another type of strategy, the deducing strategy, was most commonly used in the visualization process. Basically the participants using this strategy applied their already formed conceptual framework or gained knowledge to guide the visualization for the modeling task.

> CST2: Basically, in the biosphere, the main method of carbon cycling is through photosynthesis, and carbon is fixed in organic living things. Then the carbohydrates are used by other living things and then through respiration the carbon element goes back to the air. I am going to draw this part first.

A Level 3 performance, on the other hand, involves the use of inducting, focusing, or perfecting strategies. Compared to the deducing strategy, the inducting strategy demonstrated in the current context is considered a higher level of metavisual strategy because reflection is constantly employed to identify questions or weaknesses in the knowledge or visualization. The term “inducting” is used because the knowledge framework is organized or reconstructed during the process of visualization. For example, CST2 indicated that he is more familiar with the concepts in biology, so he started the visualization task by drawing the part related to the biosphere. It was observed (as also shown in the previous excerpt) that the visualization process was very fluent as he applied his knowledge to guide the process (the deducing strategy). Later, when he progressed to drawing the other parts of the spheres, he slowed down and used reflection such as “so the lines linking between the biosphere and atmosphere look OK,” “now it seems that I need to look up information regarding the lithosphere.” He was searching for resources and organizing his framework at the same time during the visualization process, and was therefore labeled as using the inducting strategy.

The participants demonstrating the focusing strategy paid attention to the goal of the visualization task during the process of visualization, such as “the formation is also needed (in the drawing) since the question asks about the formation of carbon compounds” (CS12), “the second part I am going to draw, is specified in the question, which is carbon cycling” (CST3), “since the question asks about cycling, I want to use text boxes to show cycles” (SST1). The participants used the focusing strategy to monitor their progress to make sure that they were achieving the goal of the task.

Some participants used the perfecting strategy during the visualization. For example, CS12 indicated “I am not sure about the biosphere and hydrosphere. Let me check…(looked up the Internet)…yes carbon dioxide can be absorbed into the ocean and can be released into the atmosphere. So the double-headed lines here are correct… May I separate these two lines?” It was observed that CS12 frequently used metacognition and epistemic knowledge of visualization to regulate her visualization process with the purpose of improving the quality of her visualization.

## 4.3 | Metavisual competence demonstrated by the teachers and students

The developed coding scheme of metavisual competence was used to code the 16 participants’ performances. Each participant was assigned to only one of the levels for each aspect, based on the highest level each person demonstrated. Also, the assignment was triangulated using different data sources including the thinking-aloud and retrospective interview data. The results are summarized in Figures 2 and 3. They provide evidence that the science teachers could be distinguished from the students in the aspects of metacognition and metavisual strategies. The science teachers were proficient in applying metacognition and metavisual strategies to aid their visualization process, whereas the performances of the students varied in the two aspects.

In terms of epistemic knowledge of visualization, most of the science teachers possessed higher levels of epistemic knowledge of visualization including Level 2 and Level 3, whereas all of the students showed only Level 1 epistemic knowledge of visualization. It is apparent that the teachers were content experts in the subject area of biology, but it does not necessarily mean that they possess the highest level of epistemic knowledge of visualization, although on average the experts did demonstrate higher levels than the novices. Similarly, in the aspect of critiquing a visualization, the content experts on average performed better than the novices. On the other hand, the majority of the students were able to critique the visualization based on the content represented in light of its

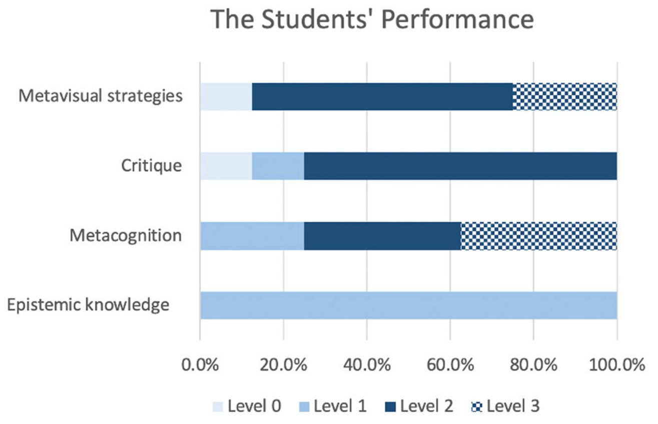


**FIGURE 2** Frequencies (in percentages) of the student's performances in the four aspects of metavisualization

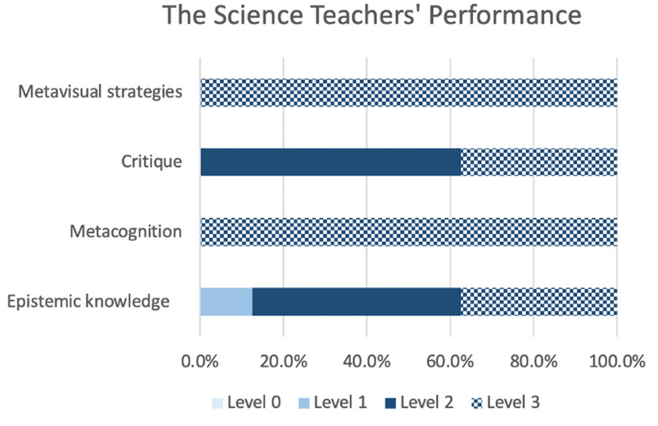


**FIGURE 3** Frequencies (in percentages) of the teacher's performances in the four aspects of metavisualization

conciseness, correctness, or completeness, whereas more science teachers critiqued the visualization considering potential readers and the purposes of the visualization.

## 5 | DISCUSSION AND CONCLUSIONS

A shift has been recognized in research from an emphasis on learning *from* representations to an emphasis on learning *with* representations across the recent 15-year period (2000–2014) (Tippett, 2016). However, very little is known about the process of students generating their own visualizations during science learning (Tippett, 2016). In the current study, eight students' processes of visualizing carbon cycling were observed and compared to another eight experienced science teachers. By the analysis of their model construction processes through the lens of the metavisualization perspectives, various performances were observed and different levels of competences were proposed. The difficulties, essential aspects, and strategies for fluent and successful construction of scientific models of carbon cycling were identified. The findings of the study contribute to research on supports for model-based learning focusing on model construction competencies and strategies, to the establishment of theories relating to metavisualization in scientific modeling based on empirical evidence, and to the implications for promoting metavisualization for scientific modeling performances, as discussed in the following.

## 5.1 | Difficulties and essential aspects for successful construction of scientific models

The current study synthesized the perspectives of metavisualization and used them as lenses to investigate the teachers' and students' visualization processes during scientific modeling of carbon cycling, which can be categorized as a type of system models (Ke et al., 2021). How the findings of the study apply to other contexts, that is, on a different science topic or with a different form of models (e.g., mathematical or textual models) requires further investigation. Nevertheless, as it is important to research issues regarding how to support students' model-based reasoning and explanations (e.g., Baumfalk et al., 2019; Forbes et al., 2015; Zangori & Forbes, 2016; Zangori et al., 2017), the study addressed an equally important issue with regard to how to support students' visualization construction during the modeling process.

By comparing the metavisualization performances of the experts (i.e., the scientists and experienced science teachers) and novices (i.e., the students), it was identified that the novices showed difficulty employing metacognition and metavisual strategies to regulate their visualization process for successful and quality visualization in the process of creating the system models. Moreover, their epistemic knowledge was limited and might demonstrate a lack of a dynamic view among visualization, knowledge reconstruction, and communication.

The epistemic knowledge of visualization is related to notions of metamodeling knowledge (Schwarz & White, 2005) and epistemic knowledge about models and modeling (Lazenby et al., 2020). The current study identified the epistemic knowledge often employed specifically in the process of visualization construction in scientific modeling, including knowledge of purposes, functions, and limitations of a visualization, knowledge of visualization strategies, and knowledge of judgment criteria for critiquing a visualization.

The investigation of epistemic knowledge of visualization in the current study highlights the importance of understanding a representation constructor's knowledge about visualization that may have been grounded in daily visualization events. It is suggested that students may bring these views which are formed in their daily life experiences to the practice of scientific modeling. Specifically, three types of epistemic knowledge of visualization have been identified, namely, a view of visualization as a learning or expression tool, a static view of representation and target, and a dynamic view between purposeful visualization and knowledge construction.

It was found in this study that all of the students possessed the view of visualization as a learning or expression tool, whereas the majority of the teachers showed the understanding of visualization in terms of the relationships between representations and their targets, and on top of that, some demonstrated a dynamic view of purposeful visualization and knowledge construction. Future research may further investigate how students possess the view that visualization as a learning or expression tool may shape their engagement and performance in the practice of scientific modeling.

Moreover, the framework of metavisualization highlights that, other than epistemic knowledge of visualization, other aspects such as metacognition, metavisual strategies, and judgment criteria, are also important to consider in the practice of scientific modeling. The finding that one of the experienced science teachers might not have previously thought about the nature of visualization in science may denote a need to investigate and develop not only students' but also science teachers' epistemic knowledge of scientific models, visualizations, and modeling.

Nevertheless, the science teachers demonstrated excellent metacognition and metavisual strategies that helped them achieve the goal of fluent visualization. These two aspects distinguished the teachers' metavisualization performances from those of the students, and therefore may be seen as two essential aspects investigated in this study, among others such as content knowledge, for successful construction of scientific models. Future interventions may consider scaffolding students to apply metacognition and metavisual strategies during their modeling practice. As the majority of research on model-based instructional interventions has addressed how students' understanding of science concepts can be promoted through the model-based approach (Campbell et al., 2015), the results of the current study indicated that it is also needed to develop students' epistemic knowledge and metacognition for successful modeling. Research on metamodeling knowledge (Schwarz & White, 2005) and epistemic knowledge about models and modeling (Lazenby et al., 2020) has identified a comprehensive list of epistemic knowledge that students need to develop. The results of the study highlight epistemic knowledge specific to the phase of visualization construction. Moreover, the comparison between the teaching experts and learning novices provides possible paths of supporting students' development, such as, from a view of visualization as a learning or expression tool to a dynamic view between purposeful visualization and knowledge construction.

## 5.2 | Learning strategies to support students' construction of scientific models

The current study identified seven types of strategies used by the participants as they constructed a model of carbon cycling, including resourcing, focusing, inducting, deducing, perfecting, intuitive drawing, and recall strategies. The former five types of strategies can be categorized as metavisual strategies since the meta-aspects including metacognition and epistemology are needed in performing these strategies. In contrast, the intuitive drawing and recall strategies are not metavisual strategies since little metacognition or epistemic knowledge of visualization is involved. Furthermore, among the five types of metavisual strategies, the resourcing or deducing strategies involve a fair amount of cognitive effort such as retrieving knowledge, searching for resources, and applying conceptual frameworks for visualization. Metacognition is also needed in these strategies, such as judging which resources or frameworks are needed, but may be only implicitly involved. In comparison, the inducting, focusing, and perfecting strategies required constant and explicit employment of metacognition and epistemic knowledge of visualization, therefore indicating a higher level of metavisual strategy use.

For example, when constructing models of carbon cycling among the four spheres of the Earth, some teachers explicitly indicated a difficulty of modeling a part that they were not familiar with, that is, the lithosphere part, due to their expertise being mainly in biology. It was observed that they used the inducting strategy through constant reflection to identify questions or weaknesses in their knowledge or visualization followed by searching for resources (e.g., knowledge of carbon cycling in the lithosphere) and organizing and integrating them to form a framework guiding their visualization of how carbon cycling occurs from and to the lithosphere. Some others used the focusing strategy through monitoring their progress to direct their focus on sufficiently representing the "cycling" part since the task asks for modeling carbon cycling. The perfecting strategy involves effort to generate a high-quality visualization. Conceptual knowledge about carbon cycling, epistemic knowledge of the scope, functions and limitations of various representations at the macroscopic, microscopic, molecular, and symbolic levels, and metacognitive regulation such as monitoring and reflecting are involved in this strategy to regulate the visualization process with the purpose of improving the quality of the visualization.

It was observed that all of the teachers in this study attained the highest level of employing metavisual strategies, using either one or several of the higher level metavisual strategies, whereas only a small portion of the students did so. As research promotes the use of metavisual strategies to enhance instruction with visualizations (Locatelli & Arroio, 2014, 2015, 2016), the identified metavisual strategies provide examples for professional development or instruction intervention. Future research may investigate whether instructing students about these metavisual strategies may promote their modeling performance.

## 5.3 | Advancement of perspectives on metavisualization

Metavisualization is a construct under development. Bringing this construct forward is necessary since researchers have noticed its important role in scientific modeling (diSessa, 2004; Gilbert, 2005, 2008). A major practice of science involves scientists constructing models, theories, and explanations of systems and phenomena (Kozma & Russell, 2005; Osborne & Quinn, 2017). Creating models involves visualizing ideas through visual, textual, and symbolic representations. The metavisualization perspectives denote key aspects to fluent and successful construction of scientific models by scientists, including employment of metacognition and epistemology (diSessa, 2004; Gilbert, 2005, 2008; Kozma & Russell, 2005). The results of this current study provide evidence that these aspects of metavisualization were constantly practiced, and metavisual competence was demonstrated by the scientists. Moreover, the various levels of the competence identified from the collection of the participants' (including the novices and experts) data may serve to indicate progressions leading to development of students' metavisual competence.

Research has also started to recognize the importance of metavisualization in learning scenarios that require students to create, interpret, or critique visualizations. For example, in model-based learning, students need to create and use models to develop theories, explain phenomena, or solve problems (Baek & Schwarz, 2015; Markauskaite et al., 2020). In learning-by-drawing activities, students engage in creating their own drawings to visualize and integrate concepts and phenomena to develop robust understanding of the subject targeted in the drawing (Ainsworth et al., 2011; Fiorella & Zhang, 2018). During online learning or in technology-rich learning environments in which visual images and visualizations are often ubiquitous, students' ability to construct, comprehend, and critique visualizations comprises an important part of literacy such as data visualization literacy (Börner et al., 2019; Donohoe & Costello, 2020).

As researchers (Eilam, 2015; Gilbert, 2008, 2010; Justi et al., 2009) suggest criteria for metavisualization that include competence at both the representational and metarepresentational levels, this current study specifically focused on the meta-aspects. This study operationalized the practice of metavisualization into four aspects, namely use of epistemic knowledge of visualization, demonstration of metacognition in visualization, use of judgment criteria to critique visualization, and use of metavisual strategies. The empirical results further exemplify the metavisualization practices in the four aspects.

Locatelli et al. (2010) and Locatelli and Davidowitz (2021) defined metavisualization as a process related to visualization and metacognition. The present study identified and provided evidence that during visualization, in addition to metacognition, individuals' epistemic knowledge of visualization, use of judgment criteria, and metavisual strategies are also important aspects to be considered and included in the metavisualization model. Furthermore, based on the variations of the participants' performances, the study proposed different levels of performance in the four aspects, indicating possible progressive levels to the development of metavisual competence that can be adapted in future research to help identify individuals' performance differences and suggested remedies.

The perspectives of metavisualization partially overlap the perspectives of metacognition and epistemology, but focus on the specific context of visualization in science and science learning. The epistemic aspect deals with ways of thinking about knowledge and knowing during the process of visualization. Such thinking can be referred to as epistemic thinking and described as meta-level thinking (Barzilai & Zohar, 2016). However, the full range and facets of epistemology were not investigated in this study, given the focus and scope limit of an investigation. The framework of epistemology has its unique systems and may be worth applying to analyze the visualization process in science learning in future studies. Nevertheless, the perspective of metavisualization provides its own framework and can be differentiated from the framework of epistemology. For example, epistemic metacognition involves the employment of metacognitive skills such as planning, monitoring, and evaluating to judge whether a desired epistemic aim has been achieved (Barzilai & Zohar, 2016). In comparison, the epistemic aspect of metavisualization stresses the necessity of applying epistemic knowledge for successful visualization. To identify epistemology from other perspectives is to consider "the issues and ends it is concerned with rather than by its form" (Barzilai & Zohar, 2016, p. 413). As metavisualization is concerned with the issue of how to achieve successful visualization, whereas epistemic metacognition is concerned with the issue of whether a desired epistemic aim has been achieved through metacognitive regulation, the two constructs can be differentiated.

## 5.4 | Attaining metavisual competence for scientific modeling in carbon cycling

In the context of constructing a model of carbon cycling, the analysis of the experts' and novices' performances in this study suggests that, to attain the metavisual competence learners need to:

- Develop a dynamic view between purposeful visualization and knowledge construction: Learners need to develop knowledge about the scope, conventions, functions and limitations of multiple representations for a given purpose; for example, in the case of modeling carbon cycling, multiple representations are often needed such as molecular representations to show how carbon atoms form compounds, macroscopic representations to show how carbon compounds exist in the ecosystems, symbolic representations to show how carbon compounds transform in the earth's spheres and so forth, so that the purpose of modeling carbon cycling can be accomplished; Learners also need to go beyond viewing visualization as merely a learning or expression tool to think about visualization as cognitive tools that may promote reconstruction of knowledge, since viewing visualization as merely a learning or expression tool may undermine the opportunities for them to take advantage of visualization to reconstruct knowledge and develop deep understanding; An example from this study is that the experts reconstructed the knowledge as prompted by the task of visualizing carbon cycling among all four spheres that they had not thought about before the study.
- Become aware of his/her difficulties and strengths in making the visualization and develop metacognitive skills to regulate the visualization process: For example, in the case of constructing a system model of carbon cycling in the four spheres, being aware of which parts of the carbon cycling that she/he has limited conceptual understanding of seems to be an important step, as demonstrated by the experts in this study. Moreover, learners need to develop metacognitive skills to regulate the visualization process; the metacognitive regulation demonstrated by the experts including planning, monitoring, and reflecting provides examples.
- Become capable of critiquing a visualization considering a set of judgment criteria including adequate content and considering readers and purposes: Learners need to go beyond critiquing based on personal preference for the appearance such as the size of a macroscopic representation. Use of judgment criteria including conciseness, correctness, or completeness is a common practice, but the experts in this study also demonstrated an even higher level by considering whether and how the visualization is adequate in light of a given purpose or for a type of reader.
- Develop and use metavisual strategies to aid the process of visualization: Learners need to go beyond using primary strategies such as the recall or imitation strategy for constructing visualization; the experts demonstrated proficient use of the metavisual strategies which can serve as examples to develop learners' strategies.

Research on representational competence in science learning has identified a range of cognitive activities and practices involving scientific representation and visualization. For example, Halverson and Friedrichsen (2013) proposed a framework of representational competence for learning biology with representations such as a phylogenetic tree. They suggest that learners must achieve the six milestones of being able to:

- Recognize and interpret informative symbolic parts of a representation.
- Compare and contrast multiple representations of similar nature, explaining why one may be more appropriate than another.
- Accurately communicate the meaning of a representation to others.
- Make predictions from a representation that supports evidence.
- Test and manipulate a representation given new scenarios or data.
- Generate appropriate and accurate representations to support evidence. (Halverson & Friedrichsen, 2013, pp. 190–191)

While the milestones focus on the important conceptual and cognitive aspects, the application of the metavisualization perspective in this study contributes to the research by identifying the epistemic and metacognitive aspects also needed for developing students' competence of learning with representation. It is evidenced in this study that learners who do not develop these metavisual competences often confront difficulties in fluent and successful construction of carbon cycling models.

## 5.5 | Lessons for the development of metavisual competence

Research has indicated that metacognitive ability is crucial for successful modeling (Chiu & Linn, 2012; diSessa, 2004; Gilbert, 2005). The results of the current study indicate that while most individuals may be aware of their own difficulties and strengths in making a visualization during a modeling task, support can be given to guide students to regulate their visualization process by planning, monitoring, and reflecting. Moreover, students might not use any metavisual strategies or may just use primary strategies such as the recall or imitation strategy during the visualization process. Instruction can be designed to guide students to learn metavisual strategies in stages, such as using the resourcing or deducing strategies to help engage them in mindful cognition, followed by using the focusing, inducting, or perfecting strategies to make use of epistemic knowledge of visualization and metacognition for quality visualization.

Research has also started to advocate the need to promote teachers' MRC (Eilam, 2015; Eilam & Gilbert, 2014; Herrlinger et al., 2017; Vijapurkar et al., 2014). The results of the current study indicate two aspects of metavisual competence that teachers may need to pay attention to, namely, their epistemic knowledge of visualization and how they applied the knowledge to form judgment criteria to critique a given visualization. Specifically, while most teachers may focus on critiquing a visualization based on the adequacy of the content represented, they may also be directed to consider problems regarding potential readers and purposes of visualization when critiquing. The highest level of metavisual competence performances can serve as anchors and concrete examples to spur discussions to promote teachers' professional development. How to integrate these findings into a professional development program or learning interventions is worth considering and trying in future studies.

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## CONFLICT OF INTEREST

The authors declare that there are no conflict of interests.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, H.-Y. Chang, upon reasonable request.

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