Schraw, G., & Richmond, A. S. (2022). Using visual displays to improve classroom thinking. *Educational Research: Theory and Practice, 33*(2), 80-102.

Using Visual Displays to Improve Classroom Thinking

Gregory Schraw[1] & Aaron S. Richmond[2]

[1]University of Nevada, Las Vegas USA
[2]Metropolitan State University of Denver USA

Author Note: *This manuscript is published by Dr. Gregory Schraw posthumously. He was a mentor, friend, and scholar who unequivocally supported NRMERA and its students. Please consider donating to the [Dr. Gregory Schraw Student Fellowship Award](). *

Abstract: *The overarching goal of this review article is to discuss and provide evidence of ways that visual displays can be used to improve classroom thinking skills. Specifically, we attempt to first, provide a synthesis of the relationship among visual displays, visual literacy, and visual thinking. Second, we review the relatively scant educational interventions used to improve the use of visual displays. Third, we discuss five ways that visual displays improve the efficiency and depth of cognitive processes, thereby enhancing the use of thinking skills. Fourth, we review research which illustrates how visual displays improve classroom thinking and deeper learning. Fifth, using the most current research, we provide a template for integrated instruction intervention for using visual displays in the classroom. This template includes the use of complementary domain-general and domain or task-specific strategies and a 12-step computer-based tutorial sequence suitable for middle school and high school students.*

Key Words: Visual displays, visual thinking, visual literacy, classroom instruction

There is a growing body of research which indicates that students who possess a general strategy for understanding visual displays (VDs), as well as display-specific strategies and conditional knowledge about when and where to use them, are more likely to understand complex information and reason about that information at a deeper level (Hegarty, 2011; Smith et al., 2002; Tufte, 2001). VDs may be defined as graphic representations of information communicated to learners (Schraw et al., 2013). They are conceptually similar and include graphical displays (e.g., Vekiri, 2002), however VDs are not limited to just graphs. Additionally, VDs can incorporate graphic organizers (e.g., Robinson, 1997) such as concept maps, story maps, advanced organizers, etc. Therefore, typical examples include data and text tables, conceptual and theoretical models, hierarchies, sequences, flowcharts, charts, stem-leaf-plots, bar graphs, concept maps, 3-D graphs, etc. Additionally, we suggest that VDs constitute a general class of information delivery graphics that include at least 14 different functional categories. Therefore, our goal in this article is to discuss ways that VDs can improve classroom thinking skills.

In this we review, we have five general goals. The first is to provide an overview of the relationship among visual literacy, visual thinking and VDs. A second goal is to provide a brief review of interventions designed to improve the students use of VDs. Surprisingly, this literature

Correspondence concerning this article should be addressed to Aaron S. Richmond, E-mail: arichmo3@msudenver.edu.

is smaller and less integrated than one might expect because specific VDs such as hierarchical trees and dendrograms tend to be used in some domain such as geological science and not in others and VDs have been used on children, older students and college students in a wide variety of settings, making it difficult at times to compare across settings. Yet despite these differences, the available research generally supports that VDs improve understanding, memory and thinking (Schraw et al., 2013). A third goal is to provide a review of studies that have used VDs to improve thinking. These studies tend to be relatively new; however, they suggest that VDs improve the targeted thinking skills used in the studies. Most of these studies can be classified as focusing on argumentation skills, problem solving, and reasoning skills. A fourth goal is to discuss reasons that VDs improve classroom thinking and deeper learning. The final goal is to provide guidelines for using VDs to improve classroom thinking through and integrated instruction intervention.

Understanding the Crucial Relationship Among Visual Literacy, Thinking, and Displays

Although there is a growing body of research which suggests that VDs can be an effective teaching tool to improve student learning (e.g., Harrell, 2011; Heiser & Tversky, 2008; McCrudden et al., 2007), in order to understand the efficacy of implementation and use of VDs, it is important to understand factors which underlie VDs. Research suggests that to use VDs successfully, individuals must possess some degree of visual literacy (e.g., Yeh & Cheng, 2010) in order to engage in visual thinking (e.g., Callister, 2009; McTigue & Flowers, 2011) and subsequently visually learn via VDs.

There has been great debate on the definition of visual literacy (e.g., Avgerinou & Ericson, 1997; Avgerinou, & Pettersson, 2011; Moore & Dwyer, 1994). However, pulling from past research, we propose that visual literacy is an important part of cognitive processes that is comprised of visual communication, visual language, visual learning, and visual thinking (see Figure 1 for illustration). Moreover, visual thinking and visual learning are influenced by use of VDs. VDs are based on visual perception and are related to and aid the development of visual learning and visual thinking skills, and ultimately the improvement of visual literacy.

For the purposes of this review, we would like to explain the key concepts to this model of visual literacy in the context of understanding and effective use of VDs. Therefore, *visual literacy*, in relation to VDs, can be further defined as the skills needed to read and write *visual language and communication*, including the ability to, (a) decode and interpret VDs, (b) encode and construct meaningful VDs, (c) visualize objects and, (d) comprehend VDs generated by others (Bamford, 2003; Yeh & Cheng, 2010). As related to VDs, visual literacy may also include conceptual elements of *diagrammatic literacy* (e.g., Stern et al., 2003), *data literacy* (e.g., the ability to use visual data to inform decisions; Mandinach & Gummer, 2013) as well as arts-based definitions of visual literacy (e.g., the ability to understand visual messages with the purpose to compose visual communications; Metros, 2008). Moreover, Schönborn and Anderson (2010) described a variety of visual literacy skills needed to understand VDs:

1. Decode the symbolic language of the VD. To do so, learners must understand the specific purpose of the VD and the symbols to depict components of the VD and relationships depicted within it.
2. Evaluate the power, limitations, and quality of the VD. This requires individuals to assess the goodness of fit between the purpose of the VD and the display itself. The main criterion is whether the display communicates clearly and accurately what it purports to communicate.

A variety of authors have proposed a set of design features a VD must possess in order to communicate with maximum efficiency and clarity (Hegarty, 2011; Lane & Sandor, 2009; Tufte, 2001).

3. Interpret or construct a VD in order to model relationships or solve a problem. Ideally, the VD does so by helping the user construct a concise mental model of the situation portrayed in the display that enables the learner to interpret the component pieces of the displays, interpret the holistic meaning, and use this information to evaluate and make inferences about what the display communicates.
4. Explain the meaning and implications of the VD in relation to broader meanings and concepts within the domain.
5. Spatially manipulate a VD to interpret and explain a concept of theory. The key conceptual activity in this step is to be able to assess and make changes to the display to improve its ability to communicate the global meaning of the display.
6. Translate across multiple VDs. This process requires analysis at the deepest possible level based on a comparison of different elements within each display.
7. Use the VD to visualize orders of magnitude, relative size, and scale. This requires the user to re-scale the display to reflect the true size and scale of elements included within it. For example, molecular biologist may greatly magnify the scale of a process in a VD to study and model the process within it.

Collectively, these competencies describe an individual with a deep set of visual literacy skills. Arriving at this point may take years of knowledge development, guided practice, and modeling of interpretation skills.

In addition to visual the visual literacy skills necessary to be successful in using VDs, previous research reports that few students of any age receive explicit instruction in visual literacy and do not possess broad visual literacy skills (Catley & Novick, 2008; Chittleborough & Treagust, 2008; Glazer, 2011; McTigue & Flowers, 2007), making it likely that students will find it difficult use complex displays or to transfer skills from one type of display to another (Gegenfurtner & Seppänen, 2013). Thus, there is a need to develop evidence-based instructional strategies to enhance both visual literacy and the effective use of VDs.

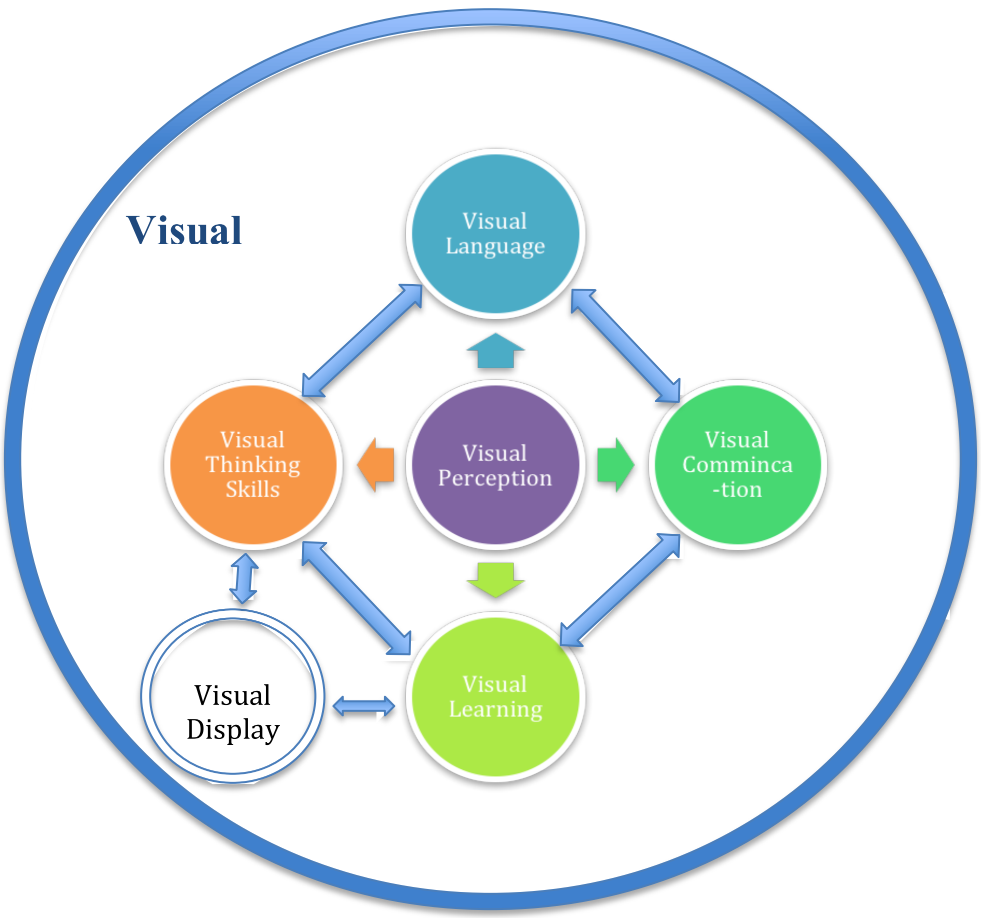
As a subset of visual literacy and in relation to VDs, *visual thinking* can be defined as the ability to conceptualize and present thoughts, ideas, and data as pictures and graphics, reducing or replacing much of the verbiage used to communicate thoughts with words (Tufte, 2001; Wileman, 1993). As illustrated in Figure 1, visual thinking is a crucial component of visual literacy because it enables individuals to understand symbolic, pictorial message and to generate (in conjuction with visual communication) such messages when useful. To do so, learners must integrate verbal and graphic symbols in VDs (Schnotz, 2002). Visual thinking skills require metaphorical though, mental models, visualization, and a properly constructed source of imagery (Moore & Dwyer, 1994). Although teaching learners to use VDs requires some degree of visual literacy and visual thinking skill, we believe these skills are teachable through explicit instruction, modeling from experts, and guided practice creating visual representations to communicate one's thoughts (Callister, 2009; McTigue & Flowers, 2011).

Underlying visual thinking skills are general thinking skills. Thinking skills encompass a variety of activities such as inductive and deductive reasoning, evaluating evidence, analyzing arguments, problem solving, formal logic, and metacognition (Byrnes & Dunbar, 2014; Holyoak & Morrison, 2005; Mayer & Wittrock, 2006; Pithers & Soden, 2000; Ricthhart & Perkins, 2005).

Some of the most common shared attributes of definitions of thinking include is that thinking is a goal-directed activity to achieve a desired outcome, requires the thinker to gather and evaluate information that is relevant to one's goal, to construct meaning and conceptual representations that can be used to analyze events around us, and to engage in strategic decision making and judgments that enhance our ability to self-regulate and prosper. But how do these general thinking skills relate to visual thinking and VDs? To clarify, we have delineated the most common types of thinking skills and how they may be used in visual thinking. We focus on three different types of thinking in this article (i.e., argumentation, reasoning, and problem solving) because there is a modest body of research that has examined how VDs affect them.

Figure 1

A Model of Visual Literacy (modified from Averginou & Petterson, 2011; Moore & Dwyer, 1994)



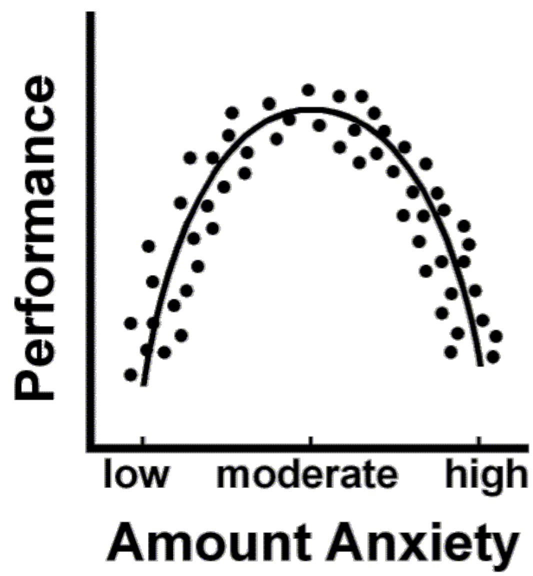
ARGUMENTATION THINKING SKILLS

One important type of thinking skill is generating and evaluating arguments (Inch & Warnick, 1998). An argument in its simplest form is a claim that supports a premise using credible evidence. For example, one might argue that fossil fuel emissions (i.e., a premise) lead to changes in weather across the planet (i.e., a claim). Argumentation is an important thinking skill that helps individuals to make claims and integrate multiple sources of evidence to support or refute a claim (Andrews, 2007). Premises and claims may take several different forms, including factual, value, and policy-based claims. Evidence also may take several forms, including pseudo, correlational, and causal evidence that differs in terms of one's ability to marshal compelling and irrefutable evidence in support of a claim (Kuhn, 1991).

Applied to VDs, argumentation skills can play a key role in understanding the accuracy and credible of VDs. To illustrate how argumentation skills can influence learning through visual displays, consider the graph in Figure 2. Figure 2 represents the curvilinear relationship between anxiety and academic performance. That is, a small amount of anxiety does increase performance, however, once you reach an asymptote of anxiety, performance no longer increase, but begins to decrease. Figure 2 illustrates an example of how anxiety is both positively and negatively correlated with performance. What if a teacher presents this graph to her psychology methods course and says, "Class, look at this figure. The figure demonstrates that anxiety CAUSES low performance." When students have strong visual literacy via the visual thinking skills of argumentation, they can recognize that the VD does not represent causation, rather, it represents the curvilinear relationship between anxiety and performance.

Figure 2

Illustrative Example of Argumentation Skills Applied to Visual Thinking and VDs



DEDUCTIVE AND INDUCTIVE REASONING THINKING SKILLS IN VDS

A second type of thinking skill necessary for visual thinking and the learning of VDs includes deductive and inductive reasoning processes. Deductive reasoning uses facts, claims, or evidence to support a conclusion. Deduction moves logically from specific evidence to a more general type of claim that may or may not be true. Many important aspects of daily life and thinking are deductive in nature, including the scientific method and hypothesis testing, the legal process in which individual s are innocent until proven guilty, and the incremental accumulation of expert knowledge that enables us to use our expertise to construct and test models of a specific phenomenon. In contrast, inductive reasoning is a process in which a verifiable conclusion is generalized to a new case. This type of reasoning moves logically from general claim that that is assumed to be true to make an inference or conjecture about an unknown case. Thus, while deductive reasoning cannot go beyond given information, inductive reasoning does so by generalizing unknown instances. Without doubt, generating inferences and generalizing beyond a specific case are two of the most important cognitive skills we engage in.

Both deductive and inductive processes are essential to sophisticated thinking, especially drawing valid conclusions based on evidence and generalizing conclusions to new cases in VDs. Take for instance the scenario described about Figure 2. Using deductive reasoning, students may deduce that the graph represents a correlational study and you cannot draw cause and effect from a correlational study. Or, inductively, students may question whether the statement made by the teacher, given the VD, is probable or likely to be true.

Problem-solving Thinking Skills in VDs

A third major type of thinking skill related to visual thinking and subsequent use of VDs is problem-solving. Problem solving usually draws on a general 5-stage strategy that includes: (1) identifying the problem, (2) representing the problem, (3) selecting an appropriate strategy, (4) implementing the strategy, and (5) evaluating solutions. This general process is used across all domains and intellectual disciplines with equal success (Novick & Bassock, 2005). Experts who study problem-solving have noted that people's ability to solve a problem depends on two crucial factors: one is the amount of domain-specific knowledge at our disposal; another is the amount of experience we have in trying to solve a particular class of problems (Mayer & Wittrock, 2006).

In the context of problem-solving and VDs, and in particular the scenario described about Figure 2, problem solving skills can be used to effectively learn from the VD. For instance, is the teachers claim about causality accurate (identify and represent problem)? The third stage would be for the student to brainstorm on how to successfully answer the teachers claim (select strategy). Next, the student may discuss the legitimacy of the claim with other students, consult a text book, draw on lecture notes, etc. (e.g., implement strategy). Finally, to assess the VD in Figure 2, the student may evaluate their solution by discussing the answer with the teacher.

Overall, the three thinking skills described previously enable individuals to use deductive and inductive processes to weigh evidence and verify conclusions, use these conclusions to generate and support claims, and engage in a multi-step problem solving process that uses evidence to identify, represent, and select appropriate strategies to solve a problem within the context of VDs and beyond. Additionally, recent research clearly indicates that thinking skills improve due to direct, systematic instruction that is embedded in an authentic context such as a science or history class that incorporates modeled instructor using problem-based learning and peer support (Burke & Williams, 2008; Ku & Ho, 2010; Lizarraga et al., 2009) and thus should be considered when designing teaching methods to improve the use of VDs in the classroom.

Before jumping into an illustrative example of visual literacy, visual thinking and VDs, it is important to understand the difference between the ability to interpret, create, and reason/think with VDs. Within the context of the visual literacy model proposed in Figure 1, the ability for students to interpret VDs lies within visual perception and visual thinking (Moore & Dwyer, 1994). Within the ability to interpret VDs, this involves the visual literacy processes/components of visual perception, visual learning, and visual thinking. For example, in Figure 2, students would need to visually perceive the graph including the X and Y axis and where the scores fall on these axes. Visual learning would involve the cognitive processes of interpreting the meaning of the scores (e.g., identifying that with low stress there is typically low performance, with moderate stress there is peak performance, and with high stress there is low performance). It would involve the intent of the teacher to visually represent a concept (e.g., illustrate a curvilinear relationship). To have student create a VD, they would primality use the processes/components of visual perception, visual communication/language, and visual thinking skills. For instance, if the teacher would ask students to replicate Figure 2 with their own example of a curvilinear relationship, they would first need to identify naturally occurring curvilinear relationships (e.g., the more sleep you get, the better reading scores you will get), then they would need to create a VD (i.e., graph as sleep increase performance increases until about 9 hours of sleep, then reading performance begins to decrease). Embedded in both the interpretation and creation of VDs, is the ability to reason or think visually. As explained previously, it would be the action of manipulating mental imagery via the visual spatial sketchpad in working memory (Moore & Dwyer, 1994) by "organizing mental images around shapes, lines, color, textures, and compositions: (Wileman, 1980, p. 13). It should be noted that the ability to interpret, create, and reason/think about VDs are not mutually exclusive tasks nor do they involve mutually exclusive visual literacy processes (Avgerinou & Ericson, 1997; Avgerinou & Pettersson, 2011; Moore & Dwyer, 1994). Rather, they are interwoven and difficult to completely parse out (Avgerinou & Pettersson, 2011).

An Illustrative Example of Visual Literacy and Visual Thinking in VDs

Now, as described previously the interplay between visual literacy, visual thinking, and visual displays is complex but necessary for successful learning. Therefore, in Figure 3, we decided to illustrate and demonstrate how visual literacy and thinking skills are necessary to understand and use a VD effectively. For example, to understand the visual display in Figure 3, 3rd grade elementary students would need to decode the symbolic language of the bar or picture graph (e.g., what to the bugs represent and what does each square represent?) as part of visual literacy. For visual literacy, they would not only need to decode, the would need to encode the meaning of a bar or picture graph (e.g., how do you know how many bugs were under logs?). Students would need to use the visual thinking skill to conceptualize "What was the least common place to find bugs?" by encoding the number of bugs that is the fewest within the different habitats (e.g., under logs). Or use the visual literacy skill of translating across multiple VDs to understand how a previous bar/picture graph can be useful in understanding this example of a bar/picture graph. Or 3rd grade students use visual thinking to create their own bar/picture graph (this combines visual literacy and skill to create VDs). As illustrated in the VD example in Figure 3, there is an intricate dance between visual literacy, visual skills and the use of VDs, but what have researchers found to help educators teach students to use VDs effectively?

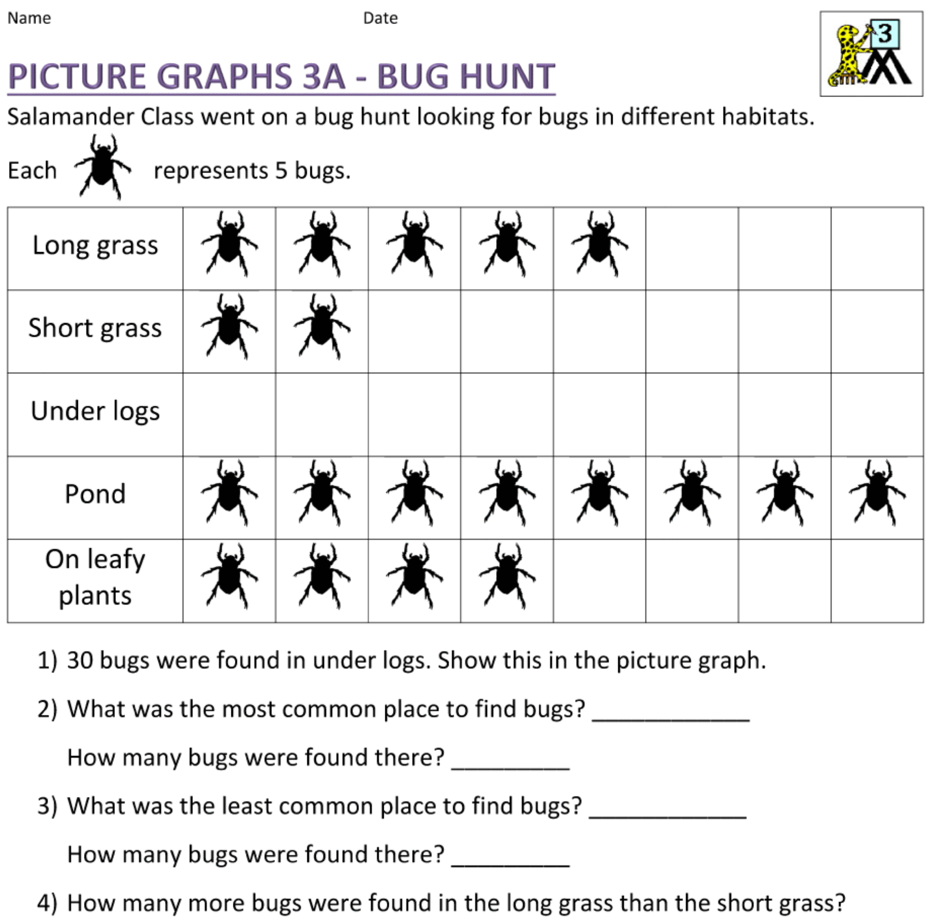
Findings from Research that Teaches Students to Use VDs

The instructional literature on VDs in classroom settings is relatively small even though displays are ubiquitous in textbooks, journals, and popular magazines (Catley & Novick, 2008; Gillen et al., 2010; Schraw et al., 2013). At present, the majority of studies in the literature focus on older students (e.g., college undergraduates) and examine either the design of VDs or the role of basic cognitive processes when reading displays such as eye fixations, visual search strategies, and optimal use of cognitive resources (e.g., Carpenter & Shah, 1998; Hegarty et al., 2010).

Most of the instructional and training research has examined note-taking formats such as linear and matrix notes (Crooks & Cheon, 2013; Moos, 2009). We also located a handful of training studies that examined data representations, conceptual models, geographical maps (Gillen et al., 2010; Liben, 2009; Scevak et al., 1993; Schwartz et al., 2007), hierarchical tree structures (Halverson et al., 2011), and causal diagrams (Jonassen & Ionas, 2008; McCrudden et al., 2007; McCrudden et al., 2011). Instructional studies have supported two findings. One is that the use of

VDs in contextually supportive learning environments yield gains for both surface (e.g., facts, simple concepts) and deeper (e.g., the integrated conceptual structure of the information, making inferences and interpretations) learning (Abrami et al., 2008; Liben, 2009; McCrudden et al., 2011; Schwonke et al., 2009; Shah & Hoeffner, 2002; van der Meer, 2012). For example, Cromley, Snyder-Hogan, and Luciw-Dubas (2010) found that students who used diagrams engaged in more meaningful strategy use and deeper cognitive processing while learning science concepts than those who used only text. Second, students who receive training performed better than those that did not using a variety of different displays (Kastens & Liben, 2007; Kwon & Cifuentes, 2009; McCrudden et al., 2007; Nesbit & Adesope, 2013; Poliquin & Schraw, 2013; Schwonke et al., 2009). Cumulatively, these research studies suggest that training may focus on three different aspects of VDs, including (a) component parts of a displays such as the role of direct and indirect in causal models, (b) the integrated conceptual structure of the display and what it is intended to convey, or (c) a repertoire of thinking skills (e.g., synthesis, hypothesis testing, making inferences) needed to fully understand displays.

Figure 3
VD Example of 3rd Grade Bar Graphing Worksheet (Math Salamanders Limited, 2016)


Name Date

PICTURE GRAPHS 3A - BUG HUNT

Salamander Class went on a bug hunt looking for bugs in different habitats.

Each represents 5 bugs.

Long grass								
Short grass								
Under logs								
Pond								
On leafy plants								

1) 30 bugs were found in under logs. Show this in the picture graph.
2) What was the most common place to find bugs? ____________
   How many bugs were found there? _________
3) What was the least common place to find bugs? ____________
   How many bugs were found there? _________
4) How many more bugs were found in the long grass than the short grass?

Research also pinpoints three serious instructional problems when VDs appear in science textbooks and technical literature. One is that displays often are unrelated to text in a clear manner with roughly 25% of displays serving a decorative purpose and another 25% being unconnected to important text themes and conclusions (Slough et al., 2010). For this reason, students may need to rely on the VD to understand the text rather than the reverse. Second, textbooks provide virtually no training for students or teachers about interpreting displays (Gillen et al., 2010; Liben, 2009). If instruction is provided at all, it likely comes piecemeal from teachers. Third, there is no general instructional framework in the literature for teaching VDs. Individual studies in the literature develop training programs based on the type of display being taught, the amount of time allocated to instruction, and the age and perceived ability of the student. Overall, we found that training differed widely across the studies we reviewed.

In summary, the literature suggests that VDs are unfamiliar to students and under-researched. Nevertheless, displays help to increase surface and deeper learning if students receive training on how to use the displays and display itself is succinct and well organized (Lane & Sandor, 2009; Tufte, 2001). We believe that training can be improved by borrowing general principles from the strategy instruction literature (Pressley & Harris, 2006). We propose subsequently an instructional framework that focuses on teaching a repertoire of (1) general learning strategies, (2) display-specific strategies, (3) a conceptually-integrated understanding of different types of VDs, (4) conditional knowledge about when and where to use different displays, and (5) discussion of the links between different types of displays and interpretation strategies that help students learn information at multiple levels of understanding, including factual, conceptual, transfer, analysis and critical interpretations of VDs. We also provide a general instructional script for teachers for guiding students through a 12-module pilot sequence and how to use displays to enhance conceptual understanding.

Findings from Research Using VDs to Improve Thinking

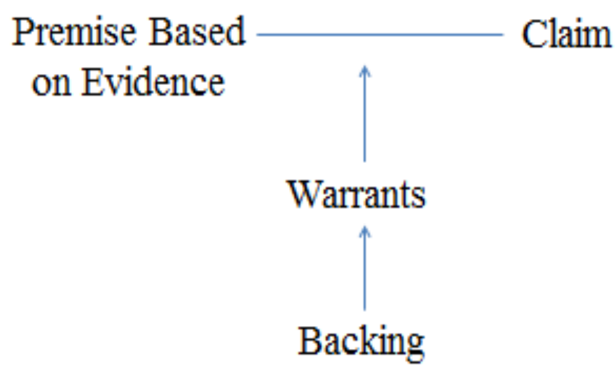
An increasing number of intervention studies have appeared that utilize some type of visual display to enhance thinking processes. It should be noted, that in the studies discussed below, that the VDs used were well define and helpful. It is possible to design and implement ineffective VDs. Or it may be a case where students have poor visual literacy and thinking skills that result in poor learning using VDs. Nonetheless, the studies we identified addressed three ways that VDs may improve thinking, including (a) teaching individuals to diagram arguments, (2) improving specific reasoning skills such as identifying and weighing evidence, (3) enhancing the problem-solving process by instantiating a problem-solving schema.

On the Importance of Diagraming Arguments

Most studies that focus on improving argumentation compare students who are taught to diagram arguments to a control group. The majority of these studies use argument diagrams based on the Toulmin (1958; as cited in Inch & Warnick, 1998) argumentation framework shown in Figure 4, which shows four components of an argument. A premise corresponds to a proposed state of affairs that is supported by credible evidence. The premise is used to support a claim, which can be defined as an opinion the argue wants accepted. The warrant describes the type of reasoning and backing used to link the premise to the claim. Finally, backing consists of additional evidence that supports the primary warrant of the argument. It should be noted that arguments may be much more complex than the single-claim arguments in Figure 4.

These studies were conducted typically in introductory science or mathematics classes and support three conclusions. One is that training students to diagram arguments significantly improves recall and the complexity of the argument by increasing the elaborative construction and warranting of the argument (Dwyer et al., 2014; Manurung et al., 2013). Argument diagramming does so by providing an explicit schema for relating the components of an argument and evaluating the credibility of evidence. Diagrams also help students utilize prior knowledge that they would not otherwise use (Ives, 2007; Salminen et al., 2010). A second conclusion is that low-achieving students benefit more from argument diagramming training than high-achieving students (Harrell, 2011), a pattern that also occurs when teaching reasoning and problem solving skills. This is due to high-achieving students already possessing implicit or explicit knowledge of an argument's components that low-achieving students do not possess. A third conclusion is that using argument diagrams during peer collaborative settings to promote deeper discussion of the argument improves construction and evaluation of the argument (van Amelsvoort et al., 2007).

Figure 4
The Toulmin Argument Diagraming Framework (1958)



ON THE IMPORTANCE OF REASONING SKILLS

Reasoning skills include a variety of specific tactics for improving thinking about complex relationships (Oliver, 2001), causal processes (Jonassen & Ionas, 2008), analogical reasoning (Cubukcu & Cetintahra, 2010), and reflective judgment (Dwyer et al., 2014). Research suggests that VDs improve reasoning in two ways. One is that the use of displays, especially with training, enhances reasoning outcomes such as analysis and reflective judgment. For example, Heiser and Tversky (2008) found that mechanical diagrams that used arrows to signal important relationships recalled more structural units than diagrams without arrows. McCrudden et al. (2007) also reported that studying a causal diagram of a complex causal process before reading a text increased recall and inferences about causal relationships, while decreasing reading time. Research suggests that VDs may be especially effective with novices (Cubukcu & Cetintahra, 2010), learning disabled (Gajria et al., 2007), and under-achieving students (Carnine & Carnine, 2014).

A second way that displays affect reasoning is to change to process of reasoning. For example, Wang and colleagues (2014) reported that concept maps that focused on the application of the scientific imagination (a form of problem-solving technique) in research affected scientific reasoning at three stages. During the *initiation stage* (i.e., idea generating to solve problem), concept maps increased brainstorming and the number and clarity of ideas about the role of scientific imagination. During the *dynamic adjustment stage* (i.e., reflect and modify solutions to solve problem), concept maps promoted both elaboration on ideas as well as transformation of ideas and solutions. In the *virtual implementation stage* (i.e., solve problem with teacher guidance), individuals appear better able to engage in conceptualizing, organizing and diagramming a revised model of scientific imagination in order to test the models' main assumptions. In general, graphic representations appear to be helpful because individuals are better able to integrate visual and verbal information into a single conceptual representation in long-term memory (Ratwani et al., 2008).

ON THE IMPORTANCE OF PROBLEM SOLVING SCHEMA

Students frequently are asked to solve different types of problems in the classroom, including word problems in mathematics and science, problems based on technical text, and graphical problems presented as equations or diagrams. VDs have been used to enhance problem solving in two ways. One is to provide a visual model (i.e., schema with component steps) of the problem-solving process to help students understand component parts and the relationship among components. As described above, many problems can be solved using strategies based on a general problem solving model that includes identifying the problem, representing the problem, selecting an appropriate strategy, implementing the strategy, and evaluating solutions (see Fink & Manley, 2010, Table 1). Providing a general problem-solving schema enhances performance and learning, especially among novices and learning-disabled students (Powell, 2011).

A second way that displays help students is to categorize problems in a specific domain such as trigonometry or calculus by different solution strategies. For example, calculus problems and corresponding solution strategies can be divided into differentiation and integration problems. In turn, integration problems can be subdivided into a variety of solution strategies such as integration by parts, integration by partial fractions, or trigonometric substitutions. As an example, Múñez and colleagues (2013) reported that students solved problems more effectively when they when first received information in a visual display about the type and difficulty of the problem, as well as appropriate strategies for different types of problems. Notably, the displays were most effective for problems of greater cognitive demand.

Overall, studies suggest that VDs help individuals improve thinking by providing a schema of the argumentation, reasoning or problem solving process. These schemata may be used as general templates and specific strategies may be linked to different types of thinking problems in the schema. Second, displays provide a bigger conceptual picture that may be used to construct meaning and evaluate solutions more effectively. Third, the use of visual diagrams is exceptionally beneficial for lower performing/under achieving, learning disabled, and novice students. Fourth, VDs have demonstrated to improve scientific reasoning. Finally, VDs can assist in identifying important information in problem solving and reducing cognitive load.

FIVE WAYS THAT VDS IMPROVE CLASSROOM THINKING AND DEEPER LEARNING

Considering the literature on visual literacy, displays, and thinking, we propose there are five ways that VDs enhance deeper learning and thinking (Dwyer et al., 2014; Hegarty, 2011; Mayer & Moreno, 2003; Schraw et al., 2013). These include (1) the optimal use of internal memory systems, (2) external representations that reduce cognitive load and free-up additional internal resources for deeper processing of information, (3) activation of prior knowledge and instantiation of new schemata, (4) use of two complementary selective processing strategies, and (5) facilitate encoding and retrieval. We first summarize these principles, then discuss in the following section how VDs may be used within a general strategy-based instructional intervention to increase thinking skills.

VDs Optimize Internal Memory Systems

One of the theoretical reasons, VDs are effective is that they optimize the use of different memory systems to process verbal and visual-spatial information most efficiently (Reed, 2006). A number of psychological theories support separate language-based and visual-spatial systems in short term memory (Baddeley et al., 2009) and long-term memory (Paivio, 1990). For example, the Baddeley model of working memory proposes three separate systems (e.g., phonological loop, visuo-spatial sketchpad, and episodic buffer) which are coordinated by a central executive processing system. One of the core assumptions of this model is that information is processed via autonomous verbal and spatial systems that utilize separate pools of cognitive resources. This means that visual processing allocated to a display may occur independent of verbal processing of a text-based representation of the same information. In turn, verbal and spatial processing is integrated by the central executive into a holistic representation that is stored in the episodic buffer. One advantage of this system is that verbal and visual processing is more efficient due to parallel processing using separate pools of resources. Cognitive load theory describes this phenomenon as the *split attention effect* in which multiple sources of information in separate documents may be processed less efficiently than integrated sources because they increase cognitive load due to switching between the sources (van Merriënboer & Sweller, 2005).

More recently, Schnotz and colleagues (Schnotz, 2002; Schnotz & Bannert, 2003) developed the integrated model of text and picture comprehension in which separate verbal and spatial systems in working memory process incoming information to construct a mental model of the information that is stored in long-term memory as intact propositional and mental model representations that made be updated on a continuous basis. The significance of this model is that it explains how a text and visual display may be processed separate during the initial stages of processing and stored as separate representations in long-term memory that nevertheless interact with each other to create a dynamic conceptual representation of the deeper meaning of the information.

Similar to working memory theory, Paivio (1990) proposed dual coding theory as an explanation for separate language-based and visual storage systems in long-term memory. The main assumption of dual coding is that information is represented in separate verbal and visual systems in long-term memory. A text with VDs, for example, may utilize both storage systems, thereby increasing the retrievability of information at a later time through multiple storage pathways.

VDs Reduce Cognitive Load

A second principle is that VDs decrease the demands of internal representation in short and long term memory by providing an external representation (Ainsworth, 2006; Hegarty, 2011). External representation promotes cognitive efficiency by off-loading information and freeing-up limited resources that can be used to analyze and interpret to-be-learned information (Lane & Sandor, 2009; Kosslyn, 1993; Moos, 2009). Off-loading helps to reduce the demands of information storage and maintenance during initial study and again at re-study by providing specific cues at encoding and retrieval. Freeing-up additional resources likewise helps the leaner to make inferences and construct mental models that are more sophisticated than they would be without the help of prior knowledge (Cook, 2005; Cook et al., 2007; Schnotz, 2002). Second, individuals use information in external representations as cues. Encoding cues help learners organize information in long-term memory, whereas retrieval cues can be used to access that information at a later time. Third, external representations help learners to understand the implicit relationships in a complex process. Oliver (2001) refers to making implicit relationships explicit through *concretization*, which can be defined as providing an explicit, organized representation of a concept or model that individuals may use to check and revise their understanding. Concretizing helps the learner to organize a variety of system components into a connected representation that transcends its individual elements, as well as to imagine ways in which complex systems and conceptual models may be transformed to increase their accuracy (Eilam & Poyas, 2010; Martin & Schwartz, 2014).

VDs Activate Prior Knowledge

A third theoretical principle is that VDs activate prior knowledge and instantiate new schemata. Activating prior knowledge from long-term memory provides useful organization information during encoding (Mayer & Wittrock, 2006). It is well known that advance organizers help learners use existing knowledge to process information more efficiently by providing background knowledge as well as a conceptual structure for organizing new information. For example, Meyer, Shinar, and Leiser (1997) reported that experts used pre-existing knowledge that novices often lacked to process information faster and more efficiency. Experts processed complex information faster than novices and also constructed more sophisticated conceptual understanding, even though both experts and novices benefitted from practice and experience.

Second, VDs may instantiate a new schema that provides an integrated mental model of a complex phenomenon. Mental models summarize the "big conceptual picture" that guides encoding and retrieval processes, and promotes deeper learning and transfer to new learning environments through the construction and refinement of the evolving mental model (Mayer, 2013; Múñez et al., 2013). In addition, mental models promote near and far transfer to new problems (Gegenfurtner & Seppänen, 2013; Ku & Ho, 2010). In the next section, we summarize the Perkins and Salomon (2012) detect-elect-connect model of transfer in which individual use existing knowledge and schemata to detect a transfer relationship between two different problem, elect to explore that relationship, and connect strategies and potential solution in one situation to another.

VDs Aid in Effective Processing Strategies

A fourth way that displays guide information processing is through two complementary selective processing strategies. The first is the effect of information relevance has on highlighting critical information. Information relevance can be defined as information that is particularly relevant or germane to the learning task, even if it is not important to the overall arguments of the text (McCrudden & Schraw, 2007). Signaling information as relevant by explicit instructions (McCrudden et al., 2011), color cueing that provides visual guidance (Hegarty et al., 2010) or animation or electronic sticky notes (De Koning et al., 2009; Mayer, 2005). Relevance increases learning because it helps individuals to set clear learning goals and prioritize relevant information for storage and retrieval. Second, by making information relevance, individuals selectively attend to relevant versus non-relevant information; thereby decreasing reading time for this information and devoting far less effort and processing to non-relevant information.

VDs Provide Encoding and Retrieval Structures

A fifth way that VDs enhance learning is by providing an integrated encoding and retrieval structure in long-term memory. Enhanced encoding refers to using the display to organize and store information in long term memory during initial processing, while refers to conducting an efficient search of memory to retrieve relevant information (Abrami et al., 2008; Mayer et al., 2002; Richardson & Ball, 2009). Learning is generally faster and better when individual study an external representation prior to reading an extended text. One reason is that an external representation provides a model of the component parts and inter-relationships among components. The learner can use this model to encode new information, and later, to retrieve the same information from memory (Ball et al., 2014; Makany et al., 2009) using retrieval cues embedded within the model for searching long-term memory.

Toward an Integrated Instruction Intervention for VDs

Building on the research on visual literacy (e.g., Bamford, 2003; Schonborn & Anderson, 2010; Yey & Cheng, 2010), visual thinking (e.g., Callister, 2009; McTigue & Flowers, 2011; Schnotz, 2002), research on how to teach students to use VDs (e.g., Catley & Novick, 2008; Schraw et al., 2013), using VDs to improve thinking (e.g., Salminen et al., 2010), and, theoretically, why VDs increase thinking and deeper learning (e.g., Dwyer et al., 2014; Hegarty, 2011), we sought to develop an integrated instruction intervention for VDs. Additionally, research suggests that teaching students to use VDs effectively, requires sequenced strategy instruction due to lack of familiarity with many types of displays and instructional support from texts (Gillen et al., 2010; Liben, 2009; Schraw et al., 2011). Two more issues of central importance emerged as well, including the scope of instruction and the choice of strategies that students are taught to self-regulate their learning. Regarding the former, instructors must choose between *stand-alone* programs which teach thinking skills independent of content and *embedded* programs which teach skills in the context of a specific content are such as algebra or biology. There has been a dramatic shift away from stand-alone programs over the last 30 years, mainly because learning new content and thinking skills simultaneously is more difficult than learning thinking skills with familiar content (Ritchhart & Perkins, 2005). Regarding issue two, researchers generally recommend instruction of both *general* and *task-specific* strategies (Lizarraga et al., 2009). General strategies help students plan and regulate their learning, while task-specific strategies focus on using displays solve specific problems; thus, these two types of strategies complement each other nicely and are consistent with evolving models of situated cognition and domain-specific expertise that emphasize general and task-specific thinking skills (Ku, 2009; Renaud & Murray, 2008).

Hattie, Biggs, and Purdie (1996) compared the rank ordering for approximately 25 general learning strategies and found the following nine to be the greatest importance: (1) self-checking, (2) creating a productive physical environment, (3) goal setting and planning, (4) generating pre-study questions, (5) reviewing and organizing information after learning, (6) summarizing during learning, (7) seeking teacher assistance, (8) seeking peer assistance, and (9) self-explanation.

Table 1 presents a 12-step, computer-based sequence of instruction we have used in local schools.

This sequence focuses on a general-to-specific instructional plan that begins with a broad overview of the sequence, a preview of general strategies, the general purpose of using VDs, and a discussion of the five cognitive principles discussed earlier in this review to help students understand how displays improve learning. At that point, instruction focuses on seven of the 14 displays to discuss, model and illustrate the design, purpose and advantages of specific displays such as data tables, causal diagrams, trends, hierarchies and sequences.

Table 1
Sequence of Tutorial Instruction in the 12-Module Sequence

Module	Topic and Purpose	Summary of Contents
1	Overview of the entire tutorial sequence.	Provide schematic overview of the tutorials, their general and individual purpose, and suggestions about how to use them.
2	Explain how and why visual displays help you learn	1. External storage. 2. Reduce cognitive load. 3. Provide new information. 4. Signal relevance of critical information. 5. Provide an integrated conceptual model. 6. Serve as a storage and retrieval structure.
3	General strategies for using visual displays	The general strategy sequence shown in Table 2 will be discussed and illustrated for students using a sample VD to model the strategies. Strategies also will be discussed by teachers who have completed the PD training.
4	Data representations	Teach the nomenclature associated with each specific type of VD; (2) Ask students to answer the following 4 questions: What information does the display provide? Do I understand the main concepts and purpose? How does the information relate to the text? What conclusions can I draw?; (3) Ask for help from others; (4) Complete mastery quiz; (5) Repeat tutorial if necessary.
5	Pictures and illustrations	Same as Step 4 using the pictures and illustrations modules.
6	Theoretical/conceptual model of a process	Same as Step 4.
7	Networks	Same as Step 4.
8	Hierarchies	Same as Step 4.
9	Causal processes and sequences	Same as Step 4.
10	Trends	Same as Step 4.
11	Common interpretative principles across VDs	Summarize common and unique features of VDs in a summary table; (2) review the general interpretative strategies; (3) discuss what type of inferences and interpretations are warranted using VDs.
12	Generating VDs on your own	Using text information to select and construct a VD to convey key ideas and relationships.

We recommend seven guidelines based on the literature for comprehensive strategy instruction (Dougherty-Stahl, 2009; Ku & Ho, 2010; Pressley & Harris, 2006), including (1) teach a core set of strategies (e.g., 4-6 in Table 2) on a continuous basis that are necessary to master the learning material (2) plan integrated instruction in advance, (3) each strategy requires explicit instruction and modelling, (4) vary the support and amount of responsibility given to students based on ongoing assessment, (5) provide cognitive feedback to students, and (6) use teacher-directed instruction followed by small group discussions to maximize learning, and (7) incorporate new problems into instruction to promote transfer of skills. We also offer three suggestions for sequencing strategy instruction. First, start broadly even in embedded programs to assure that learners understand the purpose and schematic framework for the sequence of instruction. Second, provide ample time to teach the thinking-skill sequence. In general, planning on a 6-month to 1-year time frame seems most reasonable. Third, include extensive practice as much as possible. The idea of practice as a means for developing automaticity is an important one. Researchers know that automaticity develops faster if a skill is practiced regularly, over a long period of time, and in a variety of settings. In addition, practice with a variety of different displays should increase transfer from one setting to another.

Table 2
Strategies for Using Visual Displays Effectively

Step	Activity and Purpose
1	Students review pre-tutorial guided questions that focus on the tutorial's main points and help students to construct explicit learning goals.
2	Identify type of display and intended purpose.
3	Use self-explanation to optimize the effectiveness of steps 4 through 7.
4	Identify important categories of information in the display (e.g., tree diagrams may include three main branches).
5	Evaluate relationships among categories.
6	Generate hypotheses about these relationships and use available evidence to test their plausibility.
7	Synthesize conclusions.
8	Discuss your learning with other students. Compare your learning to theirs and ask what strategies they used.
9	List two or more characteristics of the VD that facilitate learning.
10	Seek feedback from teacher and/or students before, during, or after the tutorial to clarify understanding.
11	Attempt to generate a comparable VD based on information in the text or web resources.

Task-specific strategy instruction is necessary as well to understand the specific properties of each type of display (Ku & Ho, 2010; Lane, 2013; Renaud & Murray, 2008). The research literature provides guidelines for teaching the defining characteristics of each display in the Schraw and Gutierrez 14-catergory typology (Kastens & Liben, 2007; Kwon & Cifuentes, 2009; McCrudden et al., 2007; Nesbit & Adesope, 2013; Poliquin & Schraw, 2013; Schwonke et al. 2009). To help teachers, we developed a 12-step computer-administered tutorial sequence for teaching general and task-specific components of seven of the most frequently appearing VDs in the 14-category typology shown in Tables 1 and 2. The sequence introduced three general strategy modules in Steps 1 through 3 to help leaners understand the purpose of the sequence, ways that VDs support learning and thinking, and general strategies for using and interpreting VDs. Steps 4 through 10 focus on teaching display- specific skills for seven different types of displays. Steps 11 and 12 focus on teaching interpretation skills and strategies for generating VDs. Table 2 summarizes general and specific strategies that students may use optimize the effectiveness of the instruction and learning from VDs.

Both stand-alone and embedded programs report success. Interventions focusing on embedded skills usually have infused a core set of thinking skills such as those shown in Table 1 into a specific course or content area with positive results. Davies (2006) reported the infusion of a general diagramming program that was used to create visual maps and diagrams of students' reasoning processes as used in college classes. Pre-posttest gains over a 12-week period yielded a one standard deviation gain in critical reasoning scores. In general, best results were achieved when skills were infused into an existing class via scaffolded, modeled instruction with ample opportunity for student collaboration and interaction (Buskist & Irons, 2008). The most effective programs embedded a variety of core skills (e.g., generating inferences, evaluation evidence, justify conclusions, diagramming conceptual models, generating and testing hypotheses) within the to-be-learned content and utilized extensive collaboration among students. Studies that included a follow-up phase also indicated that results persisted over time (e.g., 1 year).

Conclusions

We have argued that VDs enhance learning if students are taught how to use them. Learning improves due to five cognitive principles, including better use of memory resources, reduced load, use of prior knowledge, selective processing, and enhance encoding and retrieval. Research suggests that displays are utilized poorly in learning materials and that students receive piecemeal instruction. Nevertheless, studies that have taught students to use displays have been successful. For this reason, we advocate for more and better instruction beginning whenever students encounter displays in classroom learning materials. We believe that instruction should be embedded within the classroom and adhere to general strategy guidelines in which general and display-specific strategies are taught over an extended time frame and practiced until automated. With older students, especially those in the mathematics and science classes, an instructional sequence like that shown in Table 1 and 2 should be developed and incorporated into day-to-day content instruction for best results.

References

Abrami, P. C., Bernard, R. M., Borokhovski, E., Wade, A., Surkes, M. A., Tamim, R., & Zhang, D. (2008). Instructional interventions affecting critical thinking skills and dispositions: A stage 1 meta-analysis. *Review of Educational Research, 78,* 1102–1134. https://doi.org/10.3102/0034654308326084

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*, 183-198. doi:10.1007/s10648-014-9283-1

Andrews, R. (2007). Argumentation, critical thinking and the postgraduate dissertation. *Educational Review*, *59*(1), 1-18. http://dx.doi.org/10.1080/00131910600796777

Avgerinou, M., & Ericson, J. (1997). A review of the concept of visual literacy. *British Journal of Educational Technology*, *28*, 280-291. https://doi.org/10.1111/1467-8535.00035

Avgerinou, M. D., & Pettersson, R. (2011). Toward a cohesive theory of visual literacy. *Journal of Visual Literacy*, *30*(2), 1-19. https://doi.org/10.1080/23796529.2011.11674687

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2009). Working memory and binding in sentence recall. *Journal of Memory and Language, 61,* 438–456. https://doi.org/10.1016/j.jml.2009.05.004

Ball, B. H., DeWitt, M. R., Knight, J. B., & Hicks, J. L. (2014). Encoding and retrieval processes involved in the access of source information in the absence of item memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 1271–1286. http://dx.doi.org/10.1037/a0037204

Bamford, A. (2003). *The visual literacy white paper*. Adobe Systems.

Byrnes, J. P., & Dunbar, K. N. (2014). The nature and development of critical-analytic thinking. *Educational Psychology Review, 26,* 477-493. https://doi.org/10.1007/s10648-014-9284-0

Burke, L. A., & Williams, J. M. (2008). Developing young thinkers: An intervention aimed to enhance children's thinking skills. *Thinking Skills and Creativity, 4,* 104-124. https://doi.org/10.1016/j.tsc.2008.01.001

Buskist, W., & Irons, J. G. (2008). Simple strategies for teaching your students to think critically. In D. Dunn, J. S. Halonen & R. A. Smith (Eds), *Teaching critical thinking in psychology: A handbook of best practices* (pp. 49-57). Wiley-Blackwell.

Callister, P. D. (2009). Thinking like a research expert: Schemata for teaching complex problem-solving skills. *Legal Reference Services Quarterly, 28*, 31-51. https://doi.org/10.1080/02703190902961452

Carnine, L., & Carnine, D. (2004). The interaction of reading skills and science content knowledge when teaching struggling secondary students. *Reading & Writing Quarterly*, *20*(2), 203-218. http://dx.doi.org/10.1080/10573560490264134

Carpenter, P. A., & Shah, P. (1998). A model of the perceptual and conceptual processes in graph comprehension. *Journal of Experimental Psychology: Applied*, *4*(2), 75-100. http://dx.doi.org/10.1037/1076-898X.4.2.75

Catley, K. M., & Novick, L. R. (2008). Seeing the wood for the trees: An analysis of evolutionary diagrams in biology textbooks. *BioScience, 58,* 976-989. https://doi.org/10.1641/B581011

Chittleborough, G., & Treagust, D. (2008). Correct interpretation of chemical diagrams requires transforming from one level of representation to another. *Research in Science Education, 38*, 463–482. https://doi.org/10.1007/s11165-007-9059-4

Cook, M. (2005). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education, 90,* 1073–1091. https://doi.org/10.1002/sce.20164

Cook, M., Wiebe, E. N., & Carter, G. (2007). The influence of prior knowledge on viewing and interpreting graphics with macroscopic and molecular representations. *Science Education, 92*, 848-867. https://doi.org/10.1002/sce.20262

Cromley, J. G., Snyder-Hogan, L. E., & Luciw-Dubas, U. A. (2010). Cognitive activities in complex science text and diagrams. *Contemporary Educational Psychology*, *36,* 59–74. https://doi.org/10.1016/j.cedpsych.2009.10.002

Crooks, S. M., & Cheon, J. (2013). Strategies for note taking on computer-based graphic organizers. In G. Schraw, M. McCrudden, & D. Robinson (Eds.), *Learning through visual displays* (pp. 187-222). Information Age Publishers.

Cubukcu, E., & Cetintahra, G. E. (2010). Does analogical reasoning with visual clues affect novice and experienced design students' creativity? *Creativity Research Journal, 22,* 337–344. https://doi.org/10.1080/10400419.2010.504656

Davies, W. M. (2006). An infusion approach to critical thinking: Moore on the critical thinking debate. *Higher Education Research and Development, 2*, 179-193. https://doi.org/10.1080/07294360600610420

De Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2009). Towards a framework for attention cueing in instructional animations: Guidelines for research and design. *Educational Psychology Review*, 21, 113–140. https://doi.org/10.1007/s10648-009-9098-7

Dwyer, C. P., Hogan, M. J., & Stewart, I. (2014). An integrated critical thinking framework for the 21st century. *Thinking Skills and Creativity, 12,* 43-52. https://doi.org/10.1016/j.tsc.2013.12.004

Eilam, B., & Poyas, Y. (2010). External visual representations in science learning: The case of relations among system components. *International Journal of Science Education, 32*, 2335–2366. https://doi.org/10.1080/09500690903503096

Fink, J. M., & Mankey, G. J. (2010). A problem-solving template for integrating qualitative and quantitative physics instruction. *Journal of General Education, 59*, 273-84. https://doi.org/10.5325/jgeneeduc.59.4.0273

Gajria, M., Jitendra, A. K., Sood, S., & Sacks, G. (2007). Improving comprehension of expository text in students with LD: A research synthesis. *Journal of Learning Disabilities, 40,* 210-225. https://doi.org/10.1177/00222194070400030301

Gegenfurtner, A., & Seppänen, M. (2013). Transfer of expertise: An eye tracking and think aloud study using dynamic medical visualizations. *Computers & Education, 63*, 393–403. https://doi.org/10.1016/j.compedu.2012.12.021

Gillen, J., Skryzhevska, L., Henry, M. C., & Green, J. (2010). Map interpretation instruction in introductory textbooks: A preliminary investigation. *Journal of Geography, 109*, 181-189. https://doi.org/10.1080/00221341.2010.501381

Glazer, N. (2011). Challenges with graph interpretation: A review of the literature. *Studies in Science Education, 47*, 183–210. https://doi.org/10.1080/03057267.2011.605307

Hailey, D., Miller, A., & Yenawine, P. (2015). Understanding visual literacy: The visual thinking strategies approach. In D. M. Baylen & A. D'Alba (Eds.). *Essentials of teaching and integrating visual literacy and medial literacy.* Springer.

Halverson, K. L., Pires, C. J., & Abell, S. K. (2011). Exploring the complexity of tree thinking expertise in an undergraduate systematics. *Science Education, 95*, 794-823. https://doi.org/10.1002/sce.20436

Harrell. M. (2011). Argument diagramming and critical thinking in introductory philosophy. *Higher Education Research & Development, 30,* 371–385. https://doi.org/10.1080/07294360.2010.502559

Hattie, J., Biggs, J., & Purdie, N. (1996). Effects of learning skills interventions on student learning: A meta-analysis. *Review of Educational Research*, *66*(2), 99-136. https://doi.org/10.3102/00346543066002099

Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *Topics in Cognitive Science, 3*, 446–474. https://doi.org/10.1111/j.1756-8765.2011.01150.x

Hegarty, M., Canham, M. S., & Fabrikant, S. I. (2010). Thinking about the weather: How display salience and knowledge affect performance in a graphic inference task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 37–53. https://doi.org/10.1037/a0017683

Heiser, J., & Tversky, B. (2008). Arrows in comprehending and producing mechanical diagrams. *Cognitive Science, 30*, 581–592. https://doi.org/10.1207/s15516709cog0000_70

Holyoak, K. J., & Morrison, R. G. (Eds.) (2005). *The Cambridge handbook of thinking and reasoning.* Cambridge: Cambridge University Press.

Inch, E. S., & Warnick, B. (1998). *Critical thinking and communication: The use of reason in argument* (3rd ed.). Allyn & Bacon.

Ives, B. (2007). Graphic organizers applied to secondary algebra instruction for students with learning disorders. *Learning Disabilities Research & Practice, 22*(2), 110-118. https://doi.org/10.1111/j.1540-5826.2007.00235.x

Jonassen, D. H., & Ionas, I. G. (2008). Designing effective supports for causal reasoning. *Educational Technology Research and Development, 56*, 287–308. https://doi.org/10.1007/s11423-006-9021-6

Kastens, K. A., & Liben, L. S. (2007). Eliciting self-explanations improves children's performance on a field-based map skills task. *Cognition and Instruction, 25,* 45–74. https://doi.org/10.1080/07370000709336702

Kosslyn, S. M. (1993). *Elements of graphic design.* Freeman.

Ku, K. Y. (2009). Assessing students' critical thinking performance: Urging for measurements using multi-response formats. *Thinking Skills and Creativity, 4,* 70-76. https://doi.org/10.1016/j.tsc.2009.02.001

Ku, K. Y., & Ho, I. T. (2010). Metacognitive strategies that enhance critical thinking. *Metacognition and Learning, 5,* 251-267. https://doi.org/10.1007/s11409-010-9060-6

Kwon, S. Y., & Cifuentes, L. (2009). The comparative effect of individually-constructed vs. collaboratively-constructed computer-based concept maps. *Computers & Education, 52*, 365–375. https://doi.org/10.1016/j.compedu.2008.09.012

Kuhn, D. (1991). *The skills of argument*. Cambridge University Press.

Lane, D. M., & Sandor, A. (2009). Designing better graphs by including distributional information and integrating words, numbers, and images. *Psychological Methods, 14*, 239–257. http://dx.doi.org/10.1037/a0016620

Liben, L. S. (2009). The road to understanding maps. *Current Directions in Psychological Science, 18,* 310-315. https://doi.org/10.1111/j.1467-8721.2009.01658.x

Lizarraga, M. L., Baquedano, M. T., Mangado, T. G., & Cardelle-Elwar, M. (2009). Enhancement of thinking skills: Effects of two intervention methods. *Thinking Skills and Creativity, 4,* 30-43. https://doi.org/10.1016/j.tsc.2008.12.001

Makany, T., Kemp, J., & Dror, I. E. (2009). Optimizing the use of note-taking as an external cognitive aid for increasing learning. *British Journal of Educational Technology, 40*, 619–635. https://doi.org/10.1111/j.1467-8535.2008.00906.x

Mandinach, E. B., & Gummer, E. S. (2013). A systemic view of implementing data literacy in educator preparation. *Educational Researcher, 42*(1), 30-37. https://doi.org/10.3102/0013189X12459803

Manurung, S. R., Rustaman, N. Y., & Siregar, N. (2013). A scheme of pedagogical problem solving in kinematic to observe Toulmin argumentation feasibility. *American Institute of Physics Conference Proceedings, 1555*, 94-98. https://doi.org/10.1063/1.4821001

Martin, L., & Schwartz, D. L. (2014). A pragmatic perspective on visual representation and creative thinking. *Visual Studies, 29*, 80-93. https://doi.org/10.1080/1472586X.2014.862997

Math Salamanders Limited (2016). Free math sheets, math games, and math help: 3rd grade bar graphs. Retrieved from http://www.math-salamanders.com/bar-graphs-3rd-grade.html

Mayer, R. E. (2005). Principles for reducing extraneous processing in multimedia learning: Coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.) *The Cambridge handbook of multimedia learning* (pp. 183–212). Cambridge University Press.

Mayer, R. E. (2013). Fostering learning with visual displays. In G. Schraw, M. McCrudden & D. Robinson (Eds.), *Learning through visual displays* (pp. 47-75). Information Age Publishers.

Mayer, R. E., Mathias, A., & Wetzell, K. (2002). Fostering understanding of multimedia messages through pre-training: Evidence for a two-stage theory of mental model construction. *Journal of Experimental Psychology: Applied, 8*, 147–15. https://doi.org/10.1037/1076-898X.8.3.147

Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist, 38,* 53-52. https://doi.org/10.1207/S15326985EP3801_6

Mayer, R. E., & Wittrock, M. C. (2006). Problem solving. In P. A. Alexander & P. H. Winne (Eds.), *Handbook of Educational Psychology (2nd edition,* pp. 287-304)). Erlbaum.

McCrudden, M. T., & Schraw, G. (2007). Relevance and goal-focusing in text processing. *Educational Psychology Review, 19*, 113-139. https://doi.org/10.1007/s10648-006-9010-7

McCrudden, M. T., Schraw, G., Lehman, S., & Poliquin, A. (2007). The effect of causal diagrams on text learning. *Contemporary Educational Psychology, 32*, 367–388. https://doi.org/10.1016/j.cedpsych.2005.11.002

McCrudden, M. T., Magliano, J., & Schraw, G. (2011). The effects of diagrams on online reading processes and memory. *Discourse Processes, 48,* 69-92. https://doi.org/10.1080/01638531003694561

McTigue, E. M., & Flowers, A. C. (2011). Science visual literacy: Learners' perceptions and knowledge of diagrams. *The Reading Teacher, 64*, 578–589. https://doi.org/10.1598/RT.64.8.3

Metros, S. E. (2008). The educator's role in preparing visually literate learners. *Theory into Practice, 47*(2), 102-109. https://doi.org/10.1080/00405840801992264

Meyer, J., Shinar, D., & Leiser, D. (1997). Multiple factors that determine performance with tables and graphs. *Human Factors, 39,* 268-286. https://doi.org/10.1518/001872097778543921

Moore, D. M., & Dwyer, F. M. (Eds.) (1994). *Visual literacy: A spectrum of visual learning*. Educational Technology Publications.

Moos, D. C. (2009). Note-taking while learning hypermedia: Cognitive and motivational considerations. *Computers in Human Behavior, 25,* 1120-1128. https://doi.org/10.1016/j.chb.2009.05.004

Múñez, D., Orrantia, K. & Rosales, J. (2013). The effect of external representations on compare word problems: Supporting mental model construction. *The Journal of Experimental Education, 81*, 337-355. https://doi.org/10.1080/00220973.2012.715095

Nesbit, J. C., & Adesope, O. O. (2013). Concept maps for learning: Theory, research and design. In G. Schraw, M. McCrudden, & D. Robinson (Eds.), *Learning through visual displays* (pp. 303-328). Information Age Publishers.

Novick, L. R., & Bassock, M. (2005). Problem solving. In K Holyoak & R. G. Morrison (Eds.) *The Cambridge handbook of thinking and reasoning.* (pp. 321-349). Cambridge University Press.

Oliver, P, (2001). Diagrammatic reasoning: An artificial intelligence perspective. *Artificial Intelligence Review, 15,* 63-78. https://doi.org/10.1023/A:1006669526043

Paivio, A. (1986). *Mental representations: A dual coding approach*. Oxford University Press.

Perkins, D. N., & Salomon, G. (2012). Knowledge to go: A motivational and dispositional view of transfer. *Educational Psychologist*, *47*, 248–258. https://doi.org/10.1080/00461520.2012.693354

Pithers, R. T., & Soden, R. (2000). Critical thinking in education: A review. *Educational Research, 42,* 237-249. https://doi.org/10.1080/001318800440579

Poliquin, A., & Schraw, G. (2013). Strategy training with causal diagrams to improve text learning. In G. Schraw, M. McCrudden & D. Robinson (Eds.), *Learning through visual displays* (pp. 223-246). Information Age Publishers.

Powell, S. R. (2011). Solving word problems using schemas: A review of the literature. *Learning Disabilities Research & Practice, 26*, 94–108. https://doi.org/10.1111/j.1540-5826.2011.00329.x

Pressley, M., & Harris, K. R. (2006). Cognitive strategy instruction: from basic research to classroom instruction. In P. Alexander & P. Winne (Eds.), *Handbook of educational psychology,* 2nd edition, (pp. 265-286). Academic Press.

Ratwani, R. M., Trafton, J. G., & Boehm-Davis, D. A. (2008). Thinking graphically: Connecting vision and cognition during graph comprehension. *Journal of Experimental Psychology: Applied, 14*, 36–49. http://dx.doi.org/10.1037/1076-898X.14.1.36

Reed, S. K. (2006). Cognitive architectures for multimedia learning. *Educational Psychologist, 41,* 87-98. https://doi.org/10.1207/s15326985ep4102_2

Renaud, R. D., & Murray, H. G. (2008). A comparison of a subject-specific and general measure of critical thinking. *Thinking Skills and Creativity, 3,* 85-93. https://doi.org/10.1016/j.tsc.2008.03.005

Richardson, M., & Ball, L. J. (2009). Internal representations, external representations and ergonomics: toward a theoretical integration. *Theoretical Issues in Ergonomics Science*, *10*, 335-376. https://doi.org/10.1080/14639220802368872

Ritchhart, R., & Perkins, D. N. (2005). Learning to think: The challenges of teaching thinking. In K. J. Holyoak & R. G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (pp. 775–802). Cambridge University Press

Robinson, D. H. (1997). Graphic organizers as aids to text learning. *Literacy Research and Instruction, 37*(2), 85-105. https://doi.org/10.1080/19388079809558257

Salminen, T., Marttunen, M., & Laurinen, L. (2010). Visualizing knowledge from chat debates in argument diagrams. *Journal of Computer Assisted Learning, 26*, 379–391. https://doi.org/10.1111/j.1365-2729.2010.00354.x

Scevak, J. J., Moore, P. J., & Kirby, J. R. (1993). Training students to use maps to increase text recall. *Contemporary Educational Psychology, 18*, 401-413. https://doi.org/10.1006/ceps.1993.1030

Schnotz, W. (2002). Commentary: Towards an integrated view of learning from text and IVDs. *Educational Psychology Review, 14*, 101–120. https://doi.org/10.1023/A:1013136727916

Schnotz, W., & Bannert, M. (2003). Construction and interference in learning from multiple representations. *Learning and Instruction, 13*, 141–156. https://doi.org/10.1016/S0959-4752(02)00017-8

Schönborn, K. J., & Anderson, T. R. (2010). Bridging the educational research-teaching practice gap: Foundations for assessing and developing biochemistry students' visual literacy. *Biochemistry and Molecular Biology Education, 38,* 347–354. https://doi.org/10.1002/bmb.20436

Schraw, G., McCrudden, M. T., & Robinson, D. H. (2013). Visual displays and learning: Theoretical and practical considerations. In G. Schraw, M. McCrudden, & D. Robinson (Eds.), *Learning through visual displays* (pp. 3-19). Information Age Publishers.

Schwartz, N. L., Verdi, M. P., Morris, T., Lee, T. R., & Larson, N. K. (2007). Navigating web-based environments: Differentiating internal spatial representations from external spatial displays. *Contemporary Educational Psychology, 32*, 551–568. https://doi.org/10.1016/j.cedpsych.2007.03.004

Schwonke, R., Berthold, K., & Renkl, A. (2009). How multiple external representations are used and how they can be made more useful. *Applied Cognitive Psychology, 23*, 1227–1243. https://doi.org/10.1002/acp.1526

Shah, P., & Hoeffner, J. (2002). Review of graph comprehension research: Implications for instruction. *Educational Psychology Review, 14*, 47-69. https://doi.org/10.1023/A:1013180410169

Slough, S. W., McTigue, E. M., Kim, S., & Jennings, S. M. (2010). Science textbooks use of graphical representation: A descriptive analysis of four sixth grade science texts. *Reading Psychology, 31*, 301–325. https://doi.org/10.1080/02702710903256502

Smith, L. D., Best, L. A., Stubbs, D. A., Archibald, A. B., & Roberson-Ray, R. (2002). Constructing knowledge. The role of graphs and tables in hard and soft psychology. *American Psychologist, 57*, 749–761. http://dx.doi.org/10.1037/0003-066X.57.10.749

Stern, E., Aprea, C., & Ebner, H. G. (2003). Improving cross-content transfer in text processing by means of active graphical representation. *Learning and Instruction, 13*(2), 191-203. https://doi.org/10.1016/S0959-4752(02)00020-8

Tufte, E. R. (2001). *The visual display of quantitative information* (2nd ed.). Graphics Press.

Toulmin, S. E. (1958). *The Uses of Argument*. Cambridge: Cambridge University Press.

van Amelsvoort, M., Andriessen, J., & Kanselaar, G. (2007). Representational tools in computer-supported collaborative argumentation-based learning: How dyads work with constructed and inspected argumentative diagrams. *Journal of the Learning Sciences, 16*, 485-521. https://doi.org/10.1080/10508400701524785

van der Meer, J. (2012). Students' note-taking challenges in the twenty-first century: Considerations for teachers and academic staff developers. *Teaching in Higher Education, 17*, 13-23. https://doi.org/10.1080/13562517.2011.590974

van Merriënboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: recent developments and future directions. *Educational Psychology Review, 17*, 147–177. doi:10.1007/s10648-005-3951-0.

Vekiri, I. (2002). What is the value of graphical displays in learning?. *Educational Psychology Review, 14*(3), 261-312. https://doi.org/10.1023/A:1016064429161

Wileman, R. E. (1980). *Exercises in visual thinking*. Hastings House Publisher.

Wileman, R. E. (1993). *Visual communicating.* Educational Technology Publications.

Wang, C., Ho, H., Wu, J., & Cheng, Y. (2014). Development of the scientific imagination model: A concept-mapping perspective. *Thinking Skills and Creativity, 13*, 106–119. https://doi.org/10.1016/j.tsc.2014.04.001

Yeh, H., & Cheng, Y. (2010). The influence of the instruction of visual design principles on improving pre-service teachers' visual literacy. *Computers & Education, 54*, 244-252. https://doi.org/10.1016/j.compedu.2009.08.008