International Journal of Science Education

ISSN: 0950-0693 (Print) 1464-5289 (Online) Journal homepage: http://www.tandfonline.com/loi/tsed20

What recent research on diagrams suggests about learning with rather than learning from visual representations in science

Christine D. Tippett

INTERNATIONAL JOURNAL OF SCIENCE EDUCATION, 2016
http://dx.doi.org/10.1080/09500693.2016.1158435

What recent research on diagrams suggests about learning *with* rather than learning *from* visual representations in science

Christine D. Tippett

Faculty of Education, University of Ottawa, Ottawa, ON, Canada

ABSTRACT

The move from learning science from representations to learning science with representations has many potential and undocumented complexities. This thematic analysis partially explores the trends of representational uses in science instruction, examining 80 research studies on diagram use in science. These studies, published during 2000–2014, were located through searches of journal databases and books. Open coding of the studies identified 13 themes, 6 of which were identified in at least 10% of the studies: eliciting mental models, classroom-based research, multimedia principles, teaching and learning strategies, representational competence, and student agency. A shift in emphasis on learning with rather than learning from representations was evident across the three 5-year intervals considered, mirroring a pedagogical shift from science instruction as transmission of information to constructivist approaches in which learners actively negotiate understanding and construct knowledge. The themes and topics in recent research highlight areas of active interest and reveal gaps that may prove fruitful for further research, including classroom-based studies, the role of prior knowledge, and the use of eye-tracking. The results of the research included in this thematic review of the 2000–2014 literature suggest that both interpreting and constructing representations can lead to better understanding of science concepts.

ARTICLE HISTORY
Received 12 May 2015
Accepted 22 February 2016

KEYWORDS
Diagram; language; meta-synthesis; science literacy; visual representation

The roles of language in science education are evolving with recent discussions of disciplinary literacy and common goals across disciplines, cognitive science perspectives of learning and language as an epistemic tool, and applications of constructivist teaching approaches. Interpretations of science literacy as fundamental literacy in science, scientific understanding, and application of literacy and knowledge to participate more fully in the public debate about socio-scientific issues have recognised the communication, epistemic and persuasive roles of language and repositioned language in doing, learning and using science. Furthermore, international K-12 science education reforms have stressed the importance of constructivist perspectives of learning and teaching, scientific and

CONTACT Christine D. Tippett ctippett@uottawa.ca Faculty of Education, University of Ottawa, 145 Jean Jacques Lussier Private, Ottawa, ON, Canada, K1N 6N5

Supplemental data for this article can be accessed here http://dx.doi.org/10.1080/09500693.2016.1158435

engineering practices, and argument as central components of inquiry and design. This document analysis of studies examining visual representations, specifically diagrams, in science was undertaken to determine if the evolving definition of science literacy and a concurrent re-conceptualisation of language functions have been reflected in published science education research on visual representations. In particular, the goal was to identify possible shifts from interpretation (learning *from*) to construction (learning *with*) that might mirror the theoretical shift from taking meaning to making meaning. Additionally, this review of the empirical research literature was conducted to establish a foundation for understanding trends and emerging topics and to identify future research needs.

This study focused on 2000–2014, the transition period between the first-generation and second-generation science curriculum reforms and standards (e.g. Achieve, Inc., 2013; Australian Curriculum, Assessment and Reporting Authority, 2015; Council of Ministers of Education, Canada, 1997; Department for Education, 2013; National Governors Association Center for Best Practices & Council of Chief State School Officers, NGACBP & CCSSO, 2010; National Research Council, NRC, 1996, 2012). This 15-year period encompasses refinements to our conceptions of science literacy, including the roles of language in doing, learning and using science, and in the importance of representational competency.

Science education reforms, science literacy and science learning and teaching

The recent *Common core standards* (NGACBP & CCSSO, 2010), the *Framework for science education* (NRC, 2012), and the *Next generation science standards* (Achieve, Inc., 2013) have revitalised an interest in disciplinary literacy and cross-disciplinary learning outcomes in language, literacy, and science (NRC, 2014). International curriculum documents address aspects of language such as multiple modes of presentation and representation, use of science vocabulary, communication of ideas, incorporation of information communication technology (ICT), and selection of evidence and structuring arguments, highlighting the multiple roles that language takes in science (Hsin, Chien, Hsu, Lin, & Yore, 2016). Collectively, current science standards promote science literacy as an interacting and dynamic array of science knowledge, fundamental literacy, and the ability to participate in informed discussion of science-related issues (Yore, 2012).

Theoretical framework

Traditional language arts curricula included four strands: reading, writing, listening, and speaking. However, as ICT became more prevalent and dynamic images became more common, two new strands were added: viewing and representing (Anstey & Bull, 2006; National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010). The six strands of reading, writing, listening, speaking, viewing, and representing can be classified by function as interpreting or constructing as shown in Figure 1. The strands play essential roles in disciplinary literacy because their interaction contributes to the construction of knowledge in the disciplines and the communication of these understandings.

A growing interest in constructivist learning and teaching approaches in science classrooms has encouraged some language, literacy, and science education researchers to focus on learner-constructed text and representations to supplement the more established

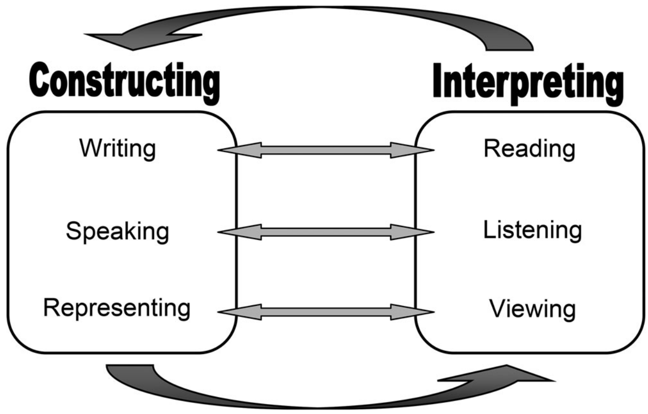

Figure 1. Six interacting language strands and their roles in constructing and interpreting meaning.

understanding of learners' interpretations of prepared science texts and representations (e.g. Tang, Delgado, & Moje, 2014). This repositioning to language construction from language processing may appear to be a minor shift, but in actuality, it represents a significant revelation in language, literacy, and science education (e.g. Ainsworth, Prain, & Tytler, 2011). Some researchers have started considering student-generated language products and representations and the constructive–interpretive nature of language pairs (talking–listening, writing–reading, representing–viewing) and the multiple functions of language in learning science (communicative, constructive, and argumentative) rather than examining only the interpretive aspects of language (e.g. listening, reading, and viewing).

Several areas of research were examined for this review, including multiple representations, multimodality, multimedia, visualisations, language in science, and representational competence. Multiple-representation research (e.g. Ainsworth, 2008; Gilbert & Treagust, 2009; Kozma, 2003) investigates the use of more than one representation at a time, although representations might be in a single sensory mode (e.g. visual representations as words, pictures, and symbols) or in multiple sensory modes (e.g. combinations of spoken words, printed images, and hands-on demonstrations or gestures). Multimodal research (e.g. Kress, 2010) might examine the use of multiple sensory modes (e.g. dramatic activities, a song about science concepts, and science information text) or the use of multiple presentation modes (e.g. verbal and nonverbal). Multimedia research (e.g. Mayer, 2001) might explore the use of multimedia technology (e.g. animations, video streaming, or computer games) or any combination of words and pictures regardless of the mode. Research in the area of visualisations (e.g. Gilbert, 2007, 2008) has explored external representations that can be seen by and shared with others. Language plays a complex role in science as scientific knowledge is constructed, argued, and communicated through a range of visual and symbolic forms (maps, graphs, charts, diagrams, formulae, models, and drawings) in addition to verbal language (e.g. Lemke, 1998). Representational competence (e.g. diSessa, 2004; Kozma & Russell, 2005) involves learners' understanding of multiple modes of representations, the creation of new representations, the conventions and traditions presented in multiple modes, the transformation between representations, and the form and function of specific aspects of representations.

Positioning representational competence in science literary

Representations afford effective communication of science ideas, and when these symbolic forms are immersed into an interactive–constructive learning environment, the emphasis moves from interpreting pre-existing forms to constructing one's own representations. The process of creating visual representations can lead to a deeper understanding of the scientific concepts being portrayed as knowledge is transformed from one mode to another (Ainsworth, 2008; Gilbert & Treagust, 2009; Pérez Echeverría, Postigo, & Pecharroman, 2010). The changing importance of visual representations in science education is evidenced in recent articles and special issues of journals not captured in earlier reviews. A 25-year review of language in science education was limited to talking, listening, reading, and writing, but did not consider representing and viewing outside of reading visual adjuncts (Yore, Bisanz, & Hand, 2003). However, recent special issues of the *International Journal of Science Education* (Visual and Spatial Modes in Science Learning, February 2009) and *Research in Science Education* (Representing Science Literacies, January 2010) have focused on using representations in science learning and teaching.

Shifting from using to constructing diagrams

Science education researchers initially explored the use of representations in science text, especially chemistry texts, to determine how students made sense of these representations of abstract ideas (e.g. Gilbert & Treagust, 2009). Other researchers have explored the use of visual representations by examining multiple representations (e.g. Eilam & Poyas, 2008; Kozma, 2003), multimedia representations (e.g. Mayer, 2001), and multimodal representations (e.g. Márquez, Izquierdo, & Espinet, 2006). The processes of creating and revising visual representations can lead to a deeper understanding of the scientific concepts being portrayed as knowledge is transformed between modes (Pérez Echeverría et al., 2010; Waldrip & Prain, 2012). However, much of the early research on representational competence in science focused on interpretation of visual representations (learning *from* representations), rather than on construction of representations (learning *with* representations).

Structure and function of language

A systemic functional linguistics (SFL) perspective illustrates how science is shaped by the language that scientists choose to use and the language that scientists use is, in turn, shaped by the specialised demands of science (Fang, 2005, 2006; Fang & Schleppegrell, 2010; Halliday & Martin, 1993; Yore, Florence, Pearson, & Weaver, 2006; Yore, Hand, & Florence, 2004). The language of science construes meaning and through that construal has developed unique grammatical and textual features, such as high lexical density (the amount of information contained in a text), abstraction, and technicality (the use of specialised terminology), and the frequent use of visual representations (Fang, 2005, 2006; Halliday, 2004; Trumbo, 2000; Unsworth, 2001).

History of research on representations

Gilbert (e.g. 1993, 2010) has long expressed the importance of models and representations in doing and learning science. This importance has been captured in international reforms and curricula (e.g. Australia, Canada, the U.K., and the U.S.A.) as both a critical science and engineering practice and an explicit learning outcome. Models facilitate construction and communication of scientific information and may serve as aids to memory or explanatory tools (Harrison & Treagust, 2000). Scientific models have integrative, predictive, and explanatory powers and they embody the essential characteristics of objects or events (Gilbert, 2007, 2010). Models can be physically represented in a range of modes or formats including scale models, equations, maps, computer simulations, and the from of visual representation of interest here: diagrams. The process of modelling involves 'self-conscious separation of a model and its referent, the explicit consideration of measurement error, and the understanding, based on analysis of model-world residuals, that alternative models are possible' (Lehrer & Schauble, 2000, p. 40). Some people refer to mental models without providing sufficient information to determine if these mental images, pictures, or visualisations are in fact models. It is important to note that not all representations are models since a representation can only be considered a scientific model when the preceding criteria are met. diSessa (2014) points out that some representations may be 'recognizably incomplete by the standards of cognitive modelling. However, they aim to provide solid empirical scaffolding for future work' (p. 798).

The lack of a well-developed framework to fully describe learner-constructed representations as a way of making sense of science concepts has been identified by a number of experts (e.g. de Vries & Lowe, 2010; Prain & Tytler, 2012). Ainsworth (2006) proposed a multidimensional model for addressing aspects of learning from multiple representations, while Carolan, Prain, and Waldrip (2008) developed a framework of pedagogical principles and more recently, Prain and Tytler (2012) suggested that representational construction affordances (RCA) might provide a framework to explain how learning is enhanced with representations. Although none of these three frameworks fully predicts or explains the interactive and constructive roles of learner-generated visual representations, each does provide a perspective on learning with visual representations.

The Design, Functions, Tasks (DeFT) conceptual framework includes several dimensions that may be influential in determining whether a learner might benefit from multiple representations, particularly in the design of educational software (Ainsworth, 2006). Design aspects include the number of representations, the way that information is apportioned to each representation, the modes of the representations, the sequence of presentation, and the relationship between representations. The functions dimension includes complementary, constraining, and constructing functions. The tasks dimension includes characteristics such as the modality (e.g. auditory, visual, written words, and diagrams), level of abstraction (e.g. symbolic or iconic), specificity (e.g. how much information is contained), and type (e.g. graph, table, written information, and picture).

A second framework, the Identify-Focus-Sequence-Ongoing Assessment (IF-SO) framework, was developed around classroom use of representations and emphasised pedagogy (Carolan et al., 2008). According to this framework, teachers need to *identify* key concepts at the planning stage and then *focus* on the form and function of the representations, clarifying conventions as necessary. The *sequence* of activities needs to include opportunities for student agency as learners represent concepts and manipulate and refine representations. The sequence also needs to address students' interests. *Ongoing assessment* can be formative or summative and should involve opportunities for students to assess their own representations.

These two frameworks are multidimensional and address a range of factors that might influence science learning. However, DeFT emphasises learning *from* a combination of representations rather than learning *with* representations and IF-SO emphasises the teacher rather than the learner. Prain and Tytler's (2012) RCA framework appears to have the most potential as a model for learning *with* representations as it includes three dimensions of meaning making: knowing about the functions of various symbolic representations, knowing when and how to use a range of symbolic representations that are specific to science, and understanding that knowing and reasoning can be enhanced by the construction and interpretation of representations.

Labelled diagrams as a specific representational form

The representational form selected for this review was limited to diagrams, because diagrams are the visual representation that students are most likely to encounter in K-12 science information texts and digital resources (Unsworth, 2004) and diagrams naturally evolve from student science practices during inquiries (NRC, 2012; Tippett, 2011). Diagrams can contain a variety of visual, symbolic, and verbal features that collectively represent an idea or event. Schnotz (2002) distinguishes between descriptive representations that are symbolic in nature (e.g. text, equations) and depictive representations that are iconic and 'are associated with the content they represent through common structural features on either a concrete or more abstract level' (p. 103). Realistic depictive representations are more concrete and the similarity between object and representation is evident (e.g. photographs and drawings). Realistic depictions can be considered polysemic (i.e. subjective and ambiguous) and non-notational (i.e. lacking one-to-one correspondence between elements and referents) and are open to interpretation (Goodman, 1968). Logical depictive representations are more abstract and characteristics of an object are indicated through spatial characteristics of a representation (e.g. maps, graphs, and schematic diagrams). They are monosemic (i.e. unambiguous and unique) or notational (i.e. possessing one-to-one correspondence between elements and referents). Labelled diagrams are depictive iconic representations having characteristics of logical and realistic depictions. They are notational and follow specific conventions based on drawings (albeit highly idealised). Drawings with labels are considered to be labelled diagrams, where the labelling emphasises the informational nature of a drawing. The function of labelled diagrams is primarily informative about processes and structures; a characteristic that distinguishes diagrams from other drawings and images (Amare & Manning, 2007). They can be used as scaffolds for knowledge construction, aids to memory, and tools for instruction (Richards, 2002).

Methods

A review of visual representation studies published between 2000 and 2014 was conducted after identification of this sweet spot in science education following several international first-generation reforms (e.g. NRC, 1996) and preceding adoption of second-generation reforms (e.g. *NGSS*, Achieve, Inc, 2013). The question underpinning the analysis was: *What patterns are evident in research on diagrams in science education, based on the peer-reviewed articles and chapters published between 2000 and 2014, and how do these patterns compare with current perspectives on language, literacy, and learning in science?* Early research on representations typically considered viewing/reading of pre-constructed representations, but taking a constructive–interpretive perspective of language moves the problem from that fairly well-defined area into an exploratory space, as comparatively little is known about what happens as students generate/construct their own visual representations. Preliminary inspection of the published literature revealed a diverse set of qualitative and quantitative research on the use of diagrams in science instruction. Therefore, since the objective of this study was to identify patterns and themes in a body of dissimilar studies with different methodologies, different contexts, and different research questions, a meta-synthesis rather than a meta-analysis was selected as the most appropriate way to review such disparate qualitative and quantitative studies (Rossman & Yore, 2009).

Procedure

An electronic search of digital databases was conducted, with an additional parameter of publication dates between 2000 and 2014. In addition, a manual search of peer-reviewed books was also conducted. While the search was not exhaustive, it was a systematic attempt to develop a conceptual review of the existing literature (Stake, 2010). An open coding procedure was applied to the final set of articles, books, and chapters in order to highlight date-sensitive trends and themes across the 15 years of publications and within three 5-year periods.

The analysis was undertaken to identify current areas of interest, emerging topics, and trends in visual representation research and highlight areas that might prove fruitful for further research. Although the analysis was limited to studies that incorporated an examination of static labelled diagrams in the context of science, those studies include multiple-representation research, multimedia studies, multimodal investigations, and explorations of computer animations. The search process was reviewed and approved by a panel of experts including science educators, literacy experts, a language and science expert, and a research methodologist.

To locate studies for inclusion in the thematic analysis, an electronic search of 66 academic databases (e.g. Academic Search Premier, ERIC, JSTOR, and PsycARTICLES) was conducted using a variety of phrases (e.g. *diagram* AND *science*, *representation* AND *science*, and *illustration* AND *science*). To supplement the electronic search, eight books on multimedia, multiple representations, and multimodal representations were manually reviewed (see supplemental online materials, Appendix A1 for a complete list) as were the annual proceedings for several international conferences that included aspects of education, science education, or visual representations. The reference lists of items that were located during the electronic and manual searches were carefully inspected. All items that were located during this phase of the search were reviewed to ensure that labelled diagrams were the topic of research, regardless of the terminology employed by the authors. This step eliminated studies that focused on representational modes such as force diagrams, ball and stick diagrams, and carpet diagrams while incorporating studies reporting on labelled drawings. The parameter of publication dates resulted in a set of articles and chapters reporting on 80 separate studies that examined the use of labelled diagrams in science. If a study was reported on more than once, only the first publication was included in the review. All studies were published in peer-reviewed books, journals, or conference proceedings and all studies were published in English.

Each study was categorised as emphasising learning *with* representations (Trend A) or learning *from* representations (Trend B). Next, each study was coded for a maximum of three words or short phrases that described the research focus and context. This step was iterative and reflective; the use of a new code would trigger a re-coding of previously coded studies. Once the initial coding process was completed, some words and phrases were identified as labels because of their high frequency of use, while others were collapsed into new labels that were more encompassing, showed relationships between foci, or were more reflective of the research focus. This final set of 13 labels was then used to re-code all 80 studies, to ensure that no research focus was missed and that all studies were coded using a consistent set of labels. The results of the coding process are shown in Table 1. A list of the 80 studies, categorised and cross-referenced by research theme and topic, is available in the supplemental online materials available with this article (Appendices A2 and A3).

Results

First, a noticeable shift in perspective about learning *from* versus learning *with* diagrams took place across the 15-year span of the analysis. Although the total number of studies that took a learning *with* view was nearly equivalent to the number of studies that took a learning *from* view over the 15-year period, the ratio of the two approaches changed drastically over three 5-year periods. Figure 2 shows the shift in trends from learning *from* pre-constructed representations to learning *with* or *through* representations. The review also revealed themes (focus of more than 10% of the studies) and topics (focus of 4–10% of the studies) as shown in Figure 3. Trends and themes are described (in

Table 1. Trends, themes, and topics in studies of diagrams in science education, 2000–2014.

		Research trend, theme, or topic	Studies *n*	Studies %
Trends[a]	A	Learning *with* diagrams	41	51.3
	B	Learning *from* diagrams	38	47.5
Themes	C	Eliciting mental models	19	23.8
	D	Classroom-based research	17	21.3
	E	Multimedia principles (incl. cognitive load)	14	17.5
	F	Teaching/learning strategies	14	17.5
	G	Representational competence	10	12.5
	H	Student agency	10	12.5
Topics	I	Assessment opportunities	7	8.8
	J	Static versus dynamic diagrams	7	8.8
	K	Eye-tracking	6	7.5
	L	Diagrams versus writing	6	7.5
	M	Prior knowledge	4	5.0
	N	Visual spatial ability	3	3.8
	O	Preference for modes	3	3.8

[a]Only 79 studies are shown in Trends, because one study examined teachers' use of representations and could not be coded as either *with* or *from*.

order of frequency) along with an overview of the studies that were coded as exemplifying the theme, and a summary of the results of those studies.

Trend A – learning with *diagrams*

The 41 studies in this category involved diagrams created by pre-kindergarten through university participants themselves, rather than pre-constructed or canonical diagrams such as those found in science information text. These studies focused on various aspects of representation including representational competence (e.g. Botzer & Reiner, 2007; Jewitt, Kress, Ogborn, & Tsatsarelis, 2001; Prain & Waldrip, 2006), student agency (e.g. Reiss, Boulter, & Tunnicliffe, 2007; Tytler, Peterson, & Prain, 2006; Tytler, Prain, & Peterson, 2007; Waldrip, Prain, & Carolan, 2010), assessment opportunities (e.g. Acher & Arcà, 2010; Best, Dockrell, Braisby, 2010; Pappas & Varelas, 2009), and learning effects (e.g. Adadan, Irving, & Trundle, 2009; Van Meter, 2001; Van Meter, Aleksic, Schwartz, & Garner, 2006).

Each study revealed insights into representational competence, learning possibilities, and instructional implications that could not have emerged from research focusing on learners making meaning from prepared diagrams. Student-generated labelled drawings can enhance observation, facilitate discussion, and encourage writing (Van Meter & Garner, 2005), suggesting that they are a useful tool for metacognition and a means of assessing students' mental models or visualisations (Adadan, Irving, & Trundle, 2009). The collective results of this group of studies suggest that learning *with* representations is a complex field of study where views of learning *from* prepared representations may not adequately explain what happens when students create their own diagrams as they learn *with* representations (Prain & Tytler, 2012). Furthermore, models such as DeFT (Ainsworth, 2006), IF-SO (Carolan et al., 2008), and RCA (Prain & Tytler, 2012) may not fully explain the intricacies of the processes and reasoning involved when students construct their own representations.

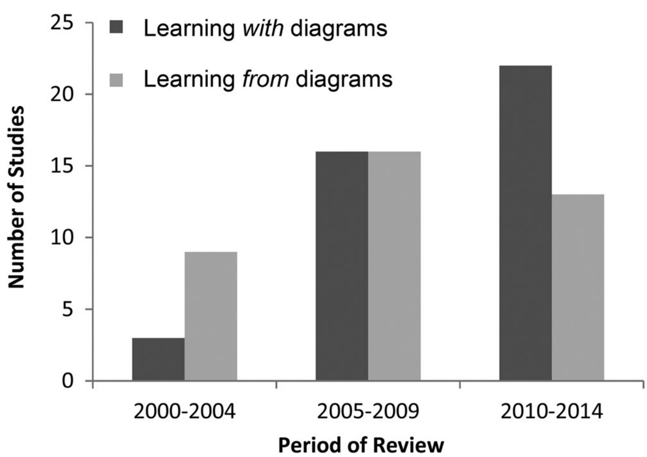

Figure 2. Trends in research examining learning *with* versus learning *from* diagrams. Only 79 studies are shown in this figure, because one study examined teachers' use of representations and could not be coded as either *with* or *from*.

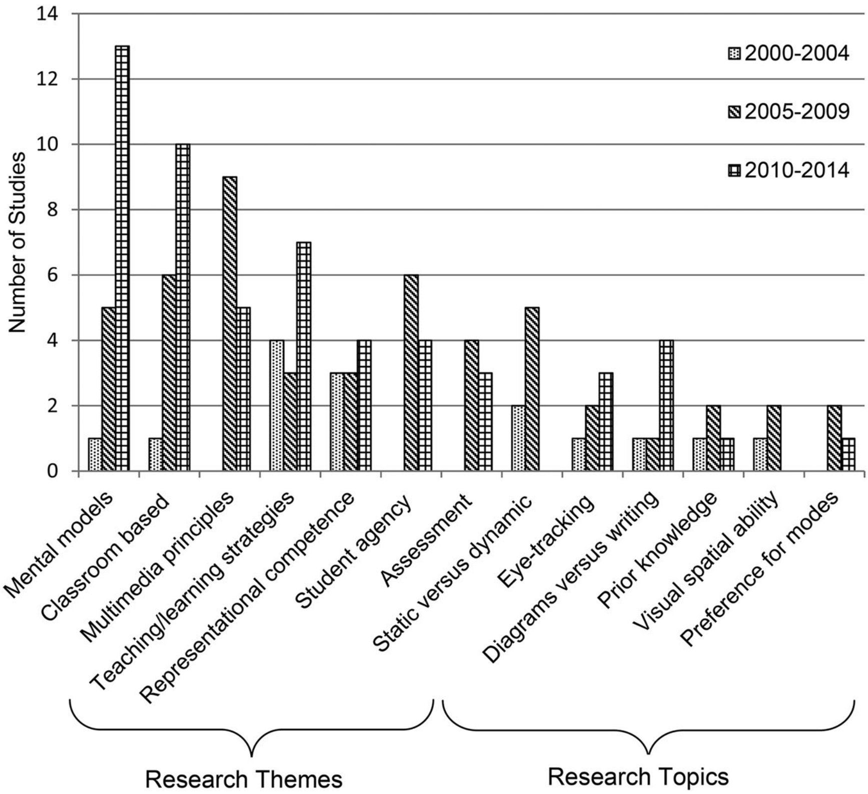

Figure 3. The frequency of research themes and topics over three 5-year spans.

Trend B – learning from *diagrams*

Learning *from* visual representations continues to be a common focus in explorations of diagram use in science, with 38 studies analysed emphasising interpretation of pre-constructed diagrams. These studies explored readers obtaining information and making interpretations from pre-constructed diagrams, which has been a central consideration since Malter (1947a, 1947b, 1948a, 1948b) reported the results of what he called a diagrammatic reading battery in which he assessed students' ability to read process diagrams, cross-sections, and conventionalised diagrammatic symbols such as lines, arrows, and dashed lines. Some studies in this category examined the form of the representation, such as colour and dimensionality (2D or 3D) (e.g. Jewitt et al., 2001), the individual symbols of diagrams (e.g. Pintó & Ametller, 2002), or the complexity of diagrams (e.g. Butcher, 2006). Other studies explored retention or transfer of the information communicated in pre-constructed diagrams (e.g. McCrudden, Schraw, Lehman, & Poliquin, 2007), strategies for learning such as augmenting diagrams with oral or written text (Harskamp, Mayer, & Suhre, 2007), comparing text in combination with diagrams, a list, or rereading text (McCrudden et al., 2007), or self-explanation (Ainsworth & Loizou, 2003).

The results of the studies exploring learning *from* diagrams appear inconclusive; in some studies, reading diagrams was reported as effective while in other studies, reading diagrams was reported to be challenging. This contradiction likely reflects the nature of the particular diagrams used, because specific aspects of diagrams, such as arrows and colour, can either facilitate or hinder learning (e.g. Pintó & Ametller, 2002; Schnotz & Bannert, 2003). Additionally, McCrudden et al. (2007) found that reading diagrams supported learning about sequences but not main ideas. Taken together, however, this group of studies highlights the influence of context, task, and form and function on the learning potential of the diagram, a large number of characteristics that may not be adequately addressed if theories of learning *from* multimedia or multimodal texts are used to explain learning *with* visual representations.

Theme C – eliciting mental models

The 19 studies in this theme focused on how student-generated diagrams were used to find out what Grade 1 to university participants knew about a particular concept. Closer inspection of these studies revealed that some of the diagrams did not possess the explanatory and predictive power of a scientific model (e.g. Lehrer & Schauble, 2000), suggesting that some models are diagrams, but not all diagrams are models. In every case, however, participants' diagrams were used as external representations of their ideas (e.g. Bamberger & Davis, 2013; Cinici, 2013).

Theme D – classroom-based research

The 17 studies in this theme were situated in classrooms, providing a much-needed perspective to the visual representation literature. Early studies of visual representations in science occurred under controlled laboratory conditions, and while those studies are informative, they do not adequately reveal the possibilities and challenges involved when working in authentic classroom settings. Although the first classroom-based studies typically focused on younger students (e.g. Grades 1–3), more recent studies have included students through Grades 11 and 12. These studies explored group negotiations of representational conventions with attendant discussions to engage and challenge students' thinking (e.g. Pappas & Varelas, 2009; Prain & Waldrip, 2006) particularly as supported by the teacher (e.g. Tytler, Peterson, & Prain, 2006; Tytler, Prain, & Peterson, 2007), investigated the assessment opportunities afforded by diagrams (e.g. Bamberger & Davis, 2013; Kukkonen, Kärkkäinen, Dillon, & Keinonen, 2014; Smith & Bermea, 2012), and examined learner-generated representations (e.g. Cromley et al., 2013; Mortimer & Buty, 2010). These results highlight the learning potential of teaching with a representational emphasis and position the critical role of the teacher in scaffolding students' representational efforts and in mediating meaningful discussions about the use of representations (e.g. Brooks, 2009; Hubber, Tytler, & Haslam, 2010; Tytler et al., 2006), and support the IF-SO (Carolan et al., 2008) and RCA (Prain & Tytler, 2012) frameworks.

Theme E – multimedia principles

The 14 studies in this theme examined various aspects of the multimedia, split-attention, coherence, and redundancy principles (Mayer, 2001), primarily with university-level participants in controlled laboratory settings. The multimedia principle states that learning can be enhanced when information is presented in two forms, particularly when pictures are added to words in a coherent fashion (Fletcher & Tobias, 2005; Mayer, 2001). The split-attention principle states that learning can be negatively affected and cognitive load increased if sources of information are not coherent and integrated spatially and temporally (Ayres & Sweller, 2005). The coherence principle states that learning is enhanced if extraneous information is excluded (Mayer, 2001). Ways to increase coherence include eliminating interesting but irrelevant details in words and representations (Mayer, 2005). The redundancy principle states that when identical information is presented in multiple forms, learning can be negatively affected (Clark & Mayer, 2011). Results of these studies inform design of visual representations or multimedia and multimodal texts, and could lead to further refinement of the DeFT framework (Ainsworth, 2006).

Theme F – teaching and learning strategies

The 14 studies in this theme emphasised the instructional affordances of learning *from* or *with* diagrams and exemplified the diverse nature of the review. Methodology included experimental, quasi-experimental, mixed methods, and qualitative approaches and participants ranged from Grade 2 students to university instructors. Some studies investigated specific strategies such as generating self-explanations when studying information in visual format (Ainsworth & Loizou, 2003; Butcher, 2006), completing unfinished diagrams (Cromley et al., 2013), mentally animating static diagrams (Hegarty, Kriz, & Cate, 2003), sequencing words and diagrams (Moreno & Valdez, 2005), using explicit scaffolding (Kukkonen et al., 2014), teaching about diagrammatic conventions (e.g. Coleman, McTigue, & Smolkin, 2011), generating inferences (Cromley, Snyder-Hogan, & Luciw-Dubas, 2010), and using diagrams as evidence to support claims (Bedward, Wiebe, Madden, Carter, & Minogue, 2009). Other studies explored learning in representation-rich environments (e.g. Padalkar & Ramadas, 2011) and teachers' attention to or use of visual representations while reading information text aloud (e.g. Coleman, Bradley, & Donovan, 2012). Results of these studies suggest that students will benefit from multiple opportunities to work with diagrams, particularly when those opportunities are supported by explicit teaching of the conventions and traditions of scientific representations (e.g. use of symbols and captions) and specific cognitive strategies (e.g. self-explaining and making inferences).

Theme G – representational competence

The 10 studies in this theme explored aspects of students' representational competence, with participants including middle school to university level students, and teachers, of Grades 2–12. Representational competence, an aspect of visual literacy that includes making decisions about appropriate types and uses of representations as well as the ability to interpret, transform, and produce visual representations to conceptualise and communicate about science concepts, is a key component of science literacy (Kozma & Russell, 2005; Nitz, Ainsworth, Nerdel, & Prechtl, 2014). Representational competence includes understanding the conventions for a range of representations and knowing how each form can and cannot be used, identifying and analysing particular features of representations, transforming and mapping between representations, creating or selecting an appropriate representation for a specific purpose, evaluating representations and justifying the appropriateness of a particular representation, inventing new representations, comparing and contrasting information obtained from different representations, solving problems using representations, and using representations to support claims, make inferences, and make predictions (diSessa, 2004; Gilbert, 2008; Kozma & Russell, 2005). These studies explored students' ability to interpret information presented in diagrams (e.g. Ametller & Pintó, 2002; Chittleborough & Treagust, 2007; Colin, Chauvet, & Viennot, 2002; Topsakal & Oversby, 2013) and their ability to produce diagrams addressing a specific purpose (e.g. Bedward et al., 2009; Waldrip et al., 2010). The results indicate that, although students might possess an intuitive understanding of representations, explicit instruction is still required in order for students to build representation and meta-representational competence (e.g. Britsch, 2013). Students may not be able to accurately gauge their own levels of competence, and teachers and instructors need to be able to assess students' abilities and provide appropriate scaffolding.

Theme H – student agency

Participants in the 10 studies in this theme ranged from Grade 1 through Grades 11 and 12. Researchers exploring student agency share the perspective that although it is important that students learn representational conventions, it is even more important that students have opportunities to consider how and why those conventions came to be (e.g. Brooks, 2009; Hubber et al., 2010). The results of these studies suggest that fostering student agency throughout the process of constructing representations tended to result in thoughtful consideration of using diagrams and other explanatory drawings (e.g. Furberg, Kluge, & Ludvigsen, 2013; Tytler et al., 2006). That consideration, in turn, likely facilitated the development of representational competence.

Topics I to O

There were eight research foci that appeared in at least three studies, but in fewer than 10% of the studies included in the analysis. These areas were deemed to be less robust than themes and were labelled topics. These topics include changes in popularity over the 15-year time period, such as the increased popularity of eye-tracking and using visual representations for assessment and areas that have waning interest, such as static versus dynamic diagrams.

Learning *with* visual representations

The 80 studies included in this review highlight the potential of constructing and interpreting diagrams for learning, thinking, and communicating about science concepts. The trends, themes, and topics identified in the studies can inform future research and help to shape classroom applications as researchers and teachers learn more about the benefits of diagrams for science learning. Diagrams (and other representations) afford multiple opportunities for teaching, learning, thinking, and communicating about science concepts, including: scaffolding for students' thinking about concepts, transformational possibilities, and assessment opportunities. The use of representations, whether the emphasis is on learning *with* or learning *from*, requires explicit instruction from the teacher and involves the use of metacognitive strategies (e.g. Brooks, 2009; Waldrip et al., 2010).

This review of research on diagrams in science reveals that from 2000 to 2014, there has been a shift towards learning *with* visual representations (i.e. enhancing understanding by constructing one's own representations and strengthening one's understanding by communicating with representations) as opposed to learning *from* those representations (i.e. interpreting representations generated by someone else). Learning *with* representations does not preclude learning *from* representations, and this broader perspective reflects a constructive–interactive view of learning where knowledge construction is an active process that involves interactions among prior knowledge, concurrent experiences, and external information resources.

Research on learning *from* representations suggests that multiple representations can foster student motivation, interest, and conceptual understanding (Treagust, 2007). Multimedia representations may be able to convey more information than either words or pictures alone (Eilam & Poyas, 2008) and may lead to increased retention of information (Mayer, 2001). When information is presented in two modes, the processing of that information can be distributed between the two systems, maximising memory resources (Ainsworth & Loizou, 2003; Moreno & Mayer, 2002). For example, diagrams used in combination with coherent print information can reduce cognitive load by presenting information in such a way that learners can use their cognitive resources more efficiently (Ainsworth & Loizou, 2003). It is likely that diagrams help learners to understand information by reducing the possible interpretations of print information. Perhaps most importantly, a diagram may depict spatial relationships that a print passage may not adequately convey (de Vries, Demetriadis, & Ainsworth, 2009).

A good deal is known about how well students can read or interpret previously constructed diagrams. However, less is known about the learning that occurs when students generate their own diagrams in order to construct knowledge, communicate ideas, and persuade others. Much of the research before 2000 provided insights into learners making sense of prepared diagrams (learning *from* representations), which was continued into the first 5-year period of this study (2000–2004), while more recently (2009–2014), there has been a shifting interest towards students constructing their own diagrams (learning *with* representations). Representations such as diagrams afford assessment opportunities and can aid students in thinking about concepts and in constructing understanding (meaning making). The transformational affordances of student-generated diagrams seem to be a key aspect of the enhanced learning that has been found when students learn science with a representational emphasis. When learners transform information from one mode to another (when they generate a diagram from inquiry experiences and observations) or one form to another (when they generate a diagram from print information), they engage with the information and are, therefore, more likely to internalise and process that information at a deeper level (e.g. Brooks, 2009). Additionally, diagrams used in combination with coherent print information appear to reduce cognitive load by presenting information in such a way that learners can use their print-based and visual-based cognitive resources more efficiently (e.g. Ainsworth & Loizou, 2003) or when younger learners use drawing as a precursor to formal writing in science (Ainsworth et al., 2011).

Taken together, the results of these 80 studies highlight the potential for the use of visual representations in learning about, thinking about, arguing about, and communicating about science concepts. Representations such as labelled diagrams afford low-pressure assessment opportunities and can aid students in thinking about concepts (e.g. Adadan et al., 2009; Pappas & Varelas, 2009). Even very young students freely talk about their diagrams and drawings (e.g. Acher & Arcà, 2010; Brooks, 2009), thereby providing more detailed information and reducing the need for interpretation and elaboration that arises when using a single source of information (e.g. Ehrlén, 2009). The results also have implications for instruction, particularly regarding the benefits and challenges of learning *with* representations (e.g. Tytler et al., 2007; Waldrip et al., 2010).

Research results suggest that students should be supported in the process of generating their own visual representations, negotiating conventions, and using those representations as tools for learning rather than as established items to be memorised (e.g. Hubber et al., 2010). The creation of representations should flow from and be accompanied by meaningful hands-on activities (e.g. Brooks, 2009; Hubber et al., 2010). To develop students' representational and meta-representational competences, teachers should mediate discussions, critiques, and evaluations of the use of representations (e.g. Waldrip et al., 2010).

From a constructive–interpretive perspective, much more research is needed on learning *with* rather than *from* representations. The circumstances in which learning *with* visual representations such as diagrams facilitates science learning need to be delineated. For example, the impact on cognitive load when learning *from* multiple modes is relatively well explored (e.g. Ayres & Sweller, 2005; Moreno & Valdez, 2005; Muller, Sharma, & Reimann, 2008), while much less is known about cognitive load and the construction of visual representations. Likewise, the roles of prior knowledge and more specialised domain knowledge in learning *with* representations are unclear, although their influence in learning *from* representations has been investigated. More research is needed to explore students' construction of representations in a variety of contexts. The relationships between task and context, and form and function, are likely important but require additional examination (Tippett, 2011); for example, it has been proposed that high levels of representational competence involve an understanding of the specific affordances of particular representations for communicating information (diSessa, 2004). Finally, more classroom-based research will enhance our understanding of what is possible in authentic learning environments.

Whether students are learning *from* or learning *with* diagrams (and other representations), instructional scaffolding needs to include conventions such as captions, labels, and the use of arrows. When learning *with* diagrams, students will develop their own methods for representing ideas through diagrams and then small group or whole class discussions can negotiate the strengths of such approaches. These discussions would also emphasise the techniques and conventions that scientists use to allow their diagrams to be interpreted by a particular audience.

With an increased emphasis on learning *with* representations, there is a need to reconsider theories that have been developed for learning *from* representations since those theories may not adequately address the factors influencing construction of representations: prior knowledge, cognition, metacognitive strategies, semiotics, SFL, and representational competence. This analysis highlights some specific areas in which further research on learning with diagrams in science is warranted, including classroom-based investigations, the effects of prior knowledge and domain knowledge, and the relationship between context, task, and form and function when learning *with* diagrams.

Closing remarks

The analysis described in this article focused on a single common representational form, the labelled diagram, and its role in science education research between 2000 and 2014. The analysis was undertaken in order to supplement earlier reviews (e.g. Vekiri, 2002) and as part of a move to inform science pedagogy by focusing on a constructive–interpretive view of language, with viewing and representing. The themes and topics in recent research highlight areas of emerging interest and reveal gaps that may prove fruitful for further research, including classroom-based studies (a recent shift in research focus that can be built upon), the role of prior knowledge (a topic that was evident throughout the three 5-year spans but with relatively few studies), and the use of eye-tracking (a relatively recent aspect, given advances in technology).

A gradual change in science education has occurred over the last 20 years since the publication of the 1994 special issue of the *Journal of Research in Science Teaching* regarding the value and role of language in doing and learning science. The 1960s' reform of science education torqued curriculum, instruction, and research in science learning and teaching towards inquiry. Unfortunately, this movement emphasised hands-on doing of science at the expense of reading, writing, viewing, and representing science, thereby discounting a powerful intellectual and communication technology—printed language and representations. Recently, several research communities have revitalised the interest in classroom discourse, writing-to-learn, and representations in doing and learning science. This revitalisation reflects the changes in views of learning theory and language and literacy research. Language is more than a communication tool; it also has epistemic/constructive and persuasive/rhetorical functions. This study indicates that these additional functions of language are being explored by many researchers within the educational psychology, ICT, language and literacy, and science education communities.

Another finding emerging from this review is the need for a sharper theoretical model that would have explanatory power when students are learning *with* visual representations such as diagrams. A great deal of research has provided insights into making sense of prepared science texts, while less is known about the learning that occurs when students generate their own representations or create texts in order to think about, construct knowledge, and communicate ideas. The results of the research included in this thematic review suggest that both interpreting and constructing representations can lead to a better understanding of science concepts. However, the existing models do not fully predict or explain the interactive and constructive aspects of learner-generated representations, nor do they acknowledge the complexities that are inherent in classroom learning conditions as compared to learning in a controlled laboratory setting.

Disclosure statement

No potential conflict of interest was reported by the author.

Funding

This research was funded in part by Pacific CRYSTAL, which was sponsored by the Natural Sciences and Engineering Research Council of Canada.

Notes on contributor

Christine D. Tippett is an Assistant Professor in the Faculty of Education at the University of Ottawa. Her engineering background influences her thinking about science education. Her research interests include visual representations, people's conceptions of scientists and engineers, and science and STEM in early childhood education.

References

Acher, A., & Arcà, M. (2010). Children's representations in modeling scientific knowledge construction. In C. Andersen, N. Scheuer, M. P. Pérez Echeverría, & E. V. Teubal (Eds.), *Representational systems and practices as learning tools* (pp. 109–131). Boston, MA: Sense.

Achieve, Inc. (2013). *Next generation science standards*. Washington, DC: The National Academies Press.

Adadan, E., Irving, K. E., & Trundle, K. C. (2009). Impacts of multi-representational instruction on high school students' conceptual understandings of the particulate nature of matter. *International Journal of Science Education*, *31*, 1743–1775. doi:10.1080/09500690802178628

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction*, *16*, 183–198. doi:10.1016/j.learninstruc.2006.03.001

Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In J. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 191–208). New York, NY: Springer.

Ainsworth, S., & Loizou, A. (2003). The effects of self-explaining when learning with text or diagrams. *Cognitive Science*, *27*, 669–681. doi:10.1207/s15516709cog2704_5

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science*, *333*, 1096–1097. doi:10.1126/science.1204153

Amare, N., & Manning, A. (2007). The language of visuals: Text + graphics = visual rhetoric. *IEEE Transactions on Professional Communication*, *50*, 57–70. doi:10.1109/TPC.2006.890851

Ametller, J., & Pintó, R. (2002). Students' reading of innovative images of energy at secondary school level. *International Journal of Science Education*, *24*, 285–312. doi:10.1080/09500690110078914

Anstey, M., & Bull, G. (2006). *Teaching and learning multiliteracies: Changing times, changing literacies*. Newark, DE: International Reading Association.

Australian Curriculum, Assessment and Reporting Authority. (2015). The Australian curriculum: Science. Retrieved from http://www.australiancurriculum.edu.au/download/f10

Ayres, P., & Sweller, J. (2005). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 135–146). New York, NY: Cambridge University Press.

Bamberger, Y. M., & Davis, E. A. (2013). Middle-school science students' scientific modelling performances across content areas and within a learning progression. *International Journal of Science Education*, *35*, 213–238. doi:10.1080/09500693.2011.624133

Bedward, J., Wiebe, E. N., Madden, L., Carter, M., & Minogue, J. (2009, April). *Graphic literacy in elementary science education: Enhancing inquiry, engineering problem-solving and reasoning skills*. Paper presented at the annual conference of the American Society for Engineering Education, Austin, TX.

Best, R., Dockrell, J., & Braisby, N. (2010). Children's semantic representations of a science term. In C. Andersen, N. Scheuer, M. P. Pérez Echeverría, & E. V. Teubal (Eds.), *Representational systems and practices as learning tools* (pp. 93–108). Boston, MA: Sense.

Botzer, G., & Reiner, M. (2007). Imagery in physics learning — from physicists' practice to naïve students' understanding. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 147–168). Dordrecht, The Netherlands: Springer.

Britsch, S. (2013). Visual language and science understanding: A brief tutorial for teachers. *Australian Journal of Language and Literacy*, *35*, 17–27.

Brooks, M. (2009). Drawing, visualisation and young children's exploration of "big ideas". *International Journal of Science Education*, *31*, 319–341. doi:10-1080/09500690802595771

Butcher, K. (2006). Learning from text with diagrams: Promoting mental model development and inference generation. *Journal of Educational Psychology*, *98*, 182–197.

Carolan, J., Prain, V., & Waldrip, B. (2008). Using representations for teaching and learning in science. *Teaching Science*, *54*, 18–23.

Chittleborough, G., & Treagust, D. F. (2007). Correct interpretation of chemical diagrams requires transforming from one level of representation to another. *Research in Science Education*, *38*, 463–482.

Cinici, A. (2013). From caterpillar to butterfly: A window for looking into students' ideas about life cycle and life forms of insects. *Journal of Biological Education*, *47*, 84–95. doi:10.1080/00219266.2013.773361

Clark, R. C., & Mayer, R. E. (2011). *E-learning and the science of instruction: Proven guidelines for consumers and designers of multimedia learning* (3rd ed.). San Francisco, CA: John Wiley & Sons.

Coleman, J. M., Bradley, L. G., & Donovan, C. A. (2012). Visual representations in second graders' information book compositions. *The Reading Teacher*, *66*, 31–45. doi:10.1002/TRTR.01100

Coleman, J. M., McTigue, E. M., & Smolkin, L. B. (2011). Elementary teachers' use of graphical representations in science teaching. *Journal of Science Teacher Education*, *22*, 612–643. doi:10.1007/s10972-010-9204-1

Colin, P., Chauvet, F., & Viennot, L. (2002). Reading images in optics: Students' difficulties and teachers' views. *International Journal of Science Education*, *24*, 313–332. doi:10.1080/09500690110078923

Council of Ministers of Education, Canada (CMEC). (1997). Common framework of science learning outcomes K to 12. Retrieved from http://publications.cmec.ca/science/framework/

Cromley, J. G., Bergey, B. W., Fitzhugh, S., Newcombe, N., Wills, T. W., Shipley, T. F., & Tanaka, J. C. (2013). Effects of three diagram instruction methods on transfer of diagram comprehension skills: The critical role of inference while learning. *Learning and Instruction*, *26*, 45–58. doi:10.1016/j.learninstruc.2013.01.003

Cromley, J. G., Snyder-Hogan, L. E., & Luciw-Dubas, U. A. (2010). Cognitive activities in complex science text and diagrams. *Contemporary Educational Psychology*, *35*, 59–74. doi:10.1016/j.cedpsych.2009.10.002

Department for Education. (2013). Science programmes of study: Key stages 1 and 2. Retrieved from https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study

diSessa, A. (2004). Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction*, *22*, 293–331. doi:10.1207/s1532690xci2203_2

diSessa, A. (2014). The construction of causal schemes: Learning mechanisms at the knowledge level. *Cognitive Science*, *38*, 795–850. doi:10.1111/cogs.12131

Ehrlén, K. (2009). Drawings as representations of children's conceptions. *International Journal of Science Education*, *31*, 41–57. doi:10.1080/09500690701630455

Eilam, B., & Poyas, Y. (2008). Learning with multiple representations: Extending multimedia learning beyond the lab. *Learning and Instruction*, *18*, 368–378. doi:10.1016/j.learninstruc.2007.07.003

Fang, Z. (2005). Scientific literacy: A systemic functional linguistics perspective. *Science Education*, *89*, 335–347. doi:10.1002/sce.20050

Fang, Z. (2006). The language demands of science reading in middle school. *International Journal of Science Education*, *5*, 491–520. doi:10.1080/09500690500339092

Fang, Z., & Schleppegrell, M. J. (2010). Disciplinary literacies across content areas: Supporting secondary reading through functional language analysis. *Journal of Adolescent and Adult Literacy*, *53*, 587–597. doi:10.1598/JAAL.53.7.6

Fletcher, J. D., & Tobias, S. (2005). The multimedia principle. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 117–133). New York, NY: Cambridge University Press.

Furberg, A., Kluge, A., & Lundvigsen, S. (2013). Student sensemaking with science diagrams in a computer-based setting. *Computer-Supported Collaborative Learning*, *8*, 41–64. doi:10.1007/s11412-013-9165-4

Gilbert, J. K. (1993). *Models and modelling in science education*. Hatfield, UK: Association for Science Education.

Gilbert, J. K. (2007). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Eds.), *Visualization in science education* (pp. 9–27). Dordrecht, The Netherlands: Springer.

Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 3–24). Dordrecht, The Netherlands: Springer.

Gilbert, J. K. (2010). The role of visual representations in the learning and teaching of science: An introduction. *Asia-Pacific Forum on Science Learning and Teaching*, *11*(1), 1–19.

Gilbert, J. K., & Treagust, D. (Eds.). (2009). *Multiple representations in chemical education*. Dordrecht, The Netherlands: Springer. doi:10.1007/978-1-4020-8872-8

Goodman, N. (1968). *The languages of art*. Indianapolis, IL: Hackett.

Halliday, M. A. K. (2004). Three aspects of children's language development: Learning language, learning through language, and learning about language (1980). In J. Webster (Ed.), *The language of early childhood* (pp. 308–326). New York, NY: Continuum.

Halliday, M. A. K., & Martin, J. (1993). *Writing science: Literacy and discursive power*. London: Falmer.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education*, *22*, 1011–1026. doi:10.1080/095006900416884

Harskamp, E. G., Mayer, R. E., & Suhre, C. (2007). Does the modality principle for multimedia learning apply to science classrooms? *Learning and Instruction*, *17*, 465–477. doi:10.1016/j.learninstruc.2007.09.010

Hegarty, M., Kriz, S., & Cate, C. (2003). The roles of mental animations and external animations in understanding mechanical systems. *Cognition and Instruction*, *21*, 325–360.

Hsin, M. C., Chien, S. P., Hsu, Y. S., Lin, C. Y., & Yore, L. D. (2016). Development and validation of a Taiwanese communication progression in science education. *International Journal of Science and Mathematics Education*, *14*(1), 125–143. doi:10.1007/s10763-014-9589-y

Hubber, P., Tytler, R., & Haslam, F. (2010). Teaching and learning about force with a representational focus: Pedagogy and teacher change. *Research in Science Education*, *40*, 5–28. doi:10.1007/s11165-009-9154-9

Jewitt, C., Kress, G., Ogborn, J., & Tsatsarelis, C. (2001). Exploring learning through visual, actional and linguistic communication: The multimodal environment of a science classroom. *Educational Review*, *53*, 5–18. doi:10.1080/00131910120033600

Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction*, *13*, 205–226. doi:10.1016/S0959-4752(02)00021-X

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualizations in Science Education* (pp. 121–146). Dordrecht, The Netherlands: Springer.

Kress, G. (2010). *Multimodality: A social semiotic approach to contemporary communication*. New York, NY: Routledge.

Kukkonen, J. E., Kärkkäinen, S., Dillon, P., & Keinonen, T. (2014). The effects of scaffolded simulation-based inquiry learning on fifth-graders' representations of the greenhouse effect. *International Journal of Science Education*, *36*, 406–424. doi:10.1080/09500693.2013.782452

Lehrer, R., & Schauble, L. (2000). Developing model-based reasoning in mathematics and science. *Journal of Applied Developmental Psychology*, *21*(1), 39–48. doi:10.1016/S0193-3973(99)00049-0

Lemke, J. (1998). Multiplying meaning: Visual and verbal semiotics in scientific text. In J. R. Martin, & R. Veel (Eds.), *Reading science: Critical and functional perspectives on discourses of science* (pp. 87–113). New York, NY: Routledge.

Malter, M. (1947a). The ability of children to read a process-diagram. *Journal of Educational Psychology*, *38*, 290–298. doi:10.1037/h0053917

Malter, M. (1947b). The ability of children to read cross-sections. *Journal of Educational Psychology*, *38*, 157–166. doi:10.1037/h0058594

Malter, M. (1948a). The ability of children to read conventionalized diagrammatic symbols. *Journal of Educational Psychology*, *39*, 27–34.

Malter, M. (1948b). Children's ability to read diagrammatic materials. *The Elementary School Journal*, *49*, 98–102.
Márquez, C., Izquierdo, M., & Espinet, M. (2006). Multimodal science teachers' discourse in modeling the water cycle. *Science Education*, *90*, 202–226.
Mayer, R. E. (2001). *Multimedia learning*. New York, NY: Cambridge University Press.
Mayer, R. E. (2005). *The Cambridge handbook of multimedia learning*. New York, NY: Cambridge University Press.
McCrudden, M., Schraw, G., Lehman, S., & Poliquin, A. (2007). The effect of causal diagrams on text learning. *Contemporary Educational Psychology*, *32*, 367–388. doi:10.1016/j.cedpsych.2005.11.002
Moreno, R., & Mayer, R. E. (2002). Verbal redundancy in multimedia learning: When reading helps listening. *Journal of Educational Psychology*, *94*, 156–163.
Moreno, R., & Valdez, A. (2005). Cognitive load and learning effects of having students organize pictures and words in multimedia environments: The role of student interactivity and feedback. *Educational Technology Research & Development*, *53*, 35–45.
Mortimer, E. F., & Buty, C. (2010). What does "in the infinite" mean? In C. Andersen, N. Scheuer, M. P. Pérez Echeverría, & E. V. Teubal (Eds.), *Representational systems and practices as learning tools* (pp. 225–242). Boston, MA: Sense.
Muller, D., Sharma, M., & Reimann, P. (2008). Raising cognitive load with linear multimedia to promote conceptual change. *Science Education*, *92*, 278–296.
National Governors Association Center for Best Practices & Council of Chief State School Officers. (2010). Common Core State Standards for English language arts and literacy in history/social studies, science, and technical subjects. Retrieved from http://www.corestandards.org/ELA-Literacy/
National Research Council. (1996). *National science education standards*. Washington, DC: National Academies Press.
National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.
National Research Council. (2014). *Literacy for science: Exploring the intersection of the next generation science standards and common core for ELA standards: A workshop summary*. Washington, DC: National Academy Press.
Nitz, S., Ainsworth, S., Nerdel, C., & Prechtl, H. (2014). Do student perceptions of teaching predict the development of representational competence and biological knowledge? *Learning & Instruction*, *31*, 13–22. doi:10.1016/j.learninstruc.2013.12.003
Padalkar, S., & Ramadas, J. (2011). Using diagrams as an effective pedagogic tool in elementary astronomy. In S. Chunawala & M. Kharatmal (Eds.), *Proceedings of epiSTEME-4 Conference, Mumbai, India* (pp. 159–164). Retrieved from http://episteme4.hbcse.tifr.res.in/proceedings
Pappas, C. C., & Varelas, M. (2009). Multimodal books in science-literacy units: Language and visual images for making meaning. *Language Arts*, *86*, 201–211.
Pérez Echeverría, M. P., Postigo, Y., & Pecharroman, A. (2010). Graphicacy: University students' skills in translating information. In C. Andersen, N. Scheuer, M. P. Pérez-Echeverría, & E. V. Teubal (Eds.), *Representational systems and practices as learning tools* (pp. 209–224). Boston, MA: Sense.
Pintó, R., & Ametller, J. (2002). Students' difficulties in reading images. Comparing results from four national research groups. *International Journal of Science Education*, *24*, 333–341. doi:10.1080/09500690110078932
Prain, V., & Tytler, R. (2012). Learning through constructing representations in science: A framework of representational construction affordances. *International Journal of Science Education*, *34*, 2751–2773.
Prain, V., & Waldrip, B. (2006). An exploratory study of teachers' and students' use of multi-modal representations of concepts in primary science. *International Journal of Science Education*, *28*, 1843–1866.

Reiss, M. J., Boulter, C., & Tunnicliffe, S. D. (2007). Seeing the natural world: A tension between pupils' diverse conceptions as revealed by their visual representations and monolithic science lessons. *Visual Communication*, *6*, 99–114.

Richards, C. (2002). The fundamental design variables of diagramming. In M. Anderson, B. Meyer, & P. Olivier (Eds.), *Diagrammatic representation and reasoning* (pp. 85–102). London: Springer.

Rossman, G. B., & Yore, L.D. (2009). Stitching the pieces together to reveal the generalized patterns: Systematic research reviews, secondary reanalyses, case-to-case comparisons, and metasyntheses of qualitative research studies. In M. C. Shelley, II., L. D. Yore, & B. Hand (Eds.), *Quality research in literacy and science education* (pp. 575–601). Dordrecht, The Netherlands: Springer.

Schnotz, W. (2002). Towards an integrated view of learning from text and visual displays. *Educational Psychology Review*, *14*(1), 102–120. doi:1040-726X/02/0300-0101/0

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

Smith, G. A., & Bermea, S. B. (2012). Using students' sketches to recognize alternative conceptions about plate tectonics persisting from prior instruction. *Journal of Geoscience Education*, *60*, 350–359. doi:1089-9995/2012/60(4)/350/10

Stake, R. E. (2010). *Qualitative research: Studying how things work*. New York, NY: Guilford.

Tang, K. S., Delgado, C., & Moje, E. B. (2014). An integrative framework for the analysis of multiple and multimodal representations for meaning-making in science education. *Science Education*, *98* (2), 305–326. doi:10.1002/sce.21099

Tippett, C. D. (2011). *Exploring middle school students' representational competence: Development and verification of a framework for learning with visual representations* (Unpublished doctoral dissertation). University of Victoria, Victoria, BC, Canada. Retrieved from https://dspace.library.uvic.ca

Topsakal, U. U., & Oversby, J. (2013). What do scientist and non-scientist teachers notice about biology diagrams? *Journal of Biological Education*, *47*, 21–28. doi:10.1080/00219266.2012.753102

Treagust, D. F. (2007). General instructional methods and strategies. In S. Abell & N. Lederman (Eds.), *Handbook of research on science education* (pp. 373–391). Mahwah, NJ: Lawrence Erlbaum.

Trumbo, J. (2000). Essay: Seeing science. *Science Communication*, *21*, 379–391.

Tytler, R., Peterson, S., & Prain, V. (2006). Picturing evaporation: Learning science literacy through a particle representation. *Teaching Science*, *52*, 12–17.

Tytler, R., Prain, V., & Peterson, S. (2007). Representational issues in students learning about evaporation. *Research in Science Education*, *37*, 313–331.

Unsworth, L. (2001). *Teaching multiliteracies across the curriculum: Changing contexts of text and image in classroom practice*. Philadelphia, PA: Open University Press.

Unsworth, L. (2004). Comparing school science explanations in books and computer-based formats: The role of images, image/text relations and hyperlinks. *International Journal of Instructional Media*, *31*, 283–301.

Van Meter, P. (2001). Drawing construction as a strategy for learning from text. *Journal of Educational Psychology*, *93*, 129–140. doi:10.1037//0022-0663.93.1.129

Van Meter, P., Aleksic, M., Schwartz, A., & Garner, J. (2006). Learner-generated drawing as a strategy for learning from content area text. *Contemporary Educational Psychology*, *31*, 142–166.

Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: Literature review and synthesis. *Educational Psychology Review*, *17*(4), 285–325.

Vekiri, I. (2002). What is the value of graphical displays in learning? *Educational Psychology Review*, *14*(3), 261–312.

de Vries, E., Demetriadis, S., & Ainsworth, S. (2009). Learning with external representations: Headed towards a digital culture. In N. Balacheff, S. Ludvigsen, T. de Jong, A. Lazonder, & S. Barnes (Eds.), *Technology enhanced learning – Principles and products* (pp. 137–153). Heidelberg, Germany: Springer.

de Vries, E., & Lowe, R. (2010). *Graphicacy: What Does the Learner Bring to a Graphic?* Paper presented at the EARLI SIG 2: Comprehension of text and graphics. Tracing the mind: How do we learn from text and graphics?, Tübingen, Germany.

Waldrip, B., & Prain, V. (2012). Learning from and through representations in science. In B. J. Fraser, K. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 145–155). Dordrecht, The Netherlands: Springer. doi:10.1007/978-1-4020-9041-7_12

Waldrip, B., Prain, V., & Carolan, J. (2010). Using multi-modal representations to improve learning in junior secondary science. *Research in Science Education*, *40*, 65–80. doi:10.1007/s11165-009-9157-6

Yore, L. D. (2012). Science literacy for all - More than a slogan, logo, or rally flag! In K. C. D. Tan, M. Kim, & S. Hwang (Eds.), *Issues and challenges in science education research: Moving forward* (pp. 5–23). Dordrecht, The Netherlands: Springer.

Yore, L. D., Bisanz, G., & Hand, B. (2003). Examining the literacy component of science literacy: 25 years of language arts and science research. *International Journal of Science Education*, *25*(6), 689–725.

Yore, L. D., Florence, M. K., Pearson, T. W., & Weaver, A. J. (2006). Written discourse in scientific communities: A conversation with two scientists about their views of science, use of language, role of writing in doing science, and compatibility between their epistemic views and language. *International Journal of Science Education*, *28*(2/3), 109–141. doi:10.1080/09500690500336601

Yore, L. D., Hand, B. M., & Florence, M. K. (2004). Scientists' views of science, models of writing, and science writing practices. *Journal of Research in Science Teaching*, *41*(4), 338–369.