How scientists develop competence in visual communication

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Abstract

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Visuals (maps, charts, diagrams and illustrations) are an important tool for communication in most scientific disciplines, which means that scientists benefit from having strong visual communication skills. This dissertation examines the nature of competence in visual communication and the means by which scientists acquire this competence. This examination takes the form of an extensive multi-disciplinary integrative literature review and a series of interviews with graduate-level science students. The results are presented as a conceptual framework that lays out the components of competence in visual communication, including the communicative goals of science visuals, the characteristics of effective visuals, the skills and knowledge needed to create effective visuals and the learning experiences that promote the acquisition of these forms of skill and knowledge. This conceptual framework can be used to inform pedagogy and thus help graduate students achieve a higher level of competency in this area; it can also be used to identify aspects of acquiring competence in visual communication that need further study.

ACKNOWLEDGEMENTS

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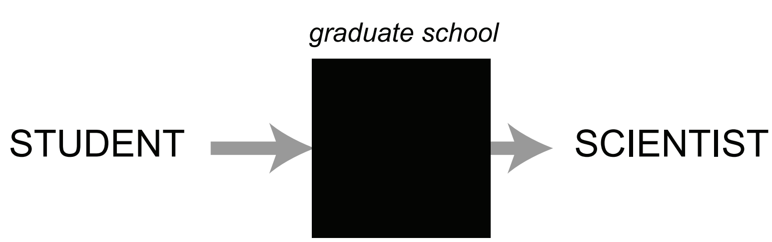
CHAPTER 1: INTRODUCTION

VISUAL COMMUNICATION AS A FORM OF PROFESSIONAL COMPETENCE

Nobel laureate Carl Wieman (2007) describes his experience with the graduate students he encounters in his lab. Despite having distinguished themselves as high-performing physics students in their undergraduate careers, they appear clueless when handed a research project. But after several years of experience in his lab, interacting with himself and lab-mates, they have somehow transformed into expert physicists and genuine colleagues.



Something has happened inside that black box labeled "graduate school" which involves more than the mastery of scientific concepts and laboratory techniques. It involves the acquisition of a range of competencies such as knowing how to collaborate effectively with other scientists, knowing how to successfully communicate research findings, and knowing how to conduct a research project from start to finish (The Science Council, 2010).

This dissertation focuses on the acquisition of one form of professional competence—*competence in visual communication*. It examines how scientists learn to create and use the non-textual, non-numeric elements of science communication such as data plots, diagrams, illustrations, and maps. These elements, referred to as *visuals* throughout this dissertation, are ubiquitous in scientific communication: "When reading scientific papers or watching presentations by scientists, nothing is more obvious than the use of visual modes of presentation for both theory and data" (Giere, 1996, p. 269). Visuals have been present in scientific journal articles since that form of communication emerged in the 17th century despite the difficulty and expense of using the reproduction technologies available at the time (woodcuts, copper etching and engravings), and they have grown in prominence ever since (Gross, Harmon, & Reidy, 2002). Some have even argued that visuals played a pivotal role in enabling the emergence of modern science by facilitating new modes of thought and new modes of disseminating ideas (Edgerton, 1985; Bruno Latour, 1986). David Knight suggests that visuals are indispensible in the physical sciences and chemistry: "without the visual language, the material would be unintelligible" (1996, p. 135). Martin Rudwick describes the emergence of geology as a scientific discipline as going hand-in-hand with the development of a distinct visual language (Rudwick, 1976).

Despite the importance of visuals in science, the acquisition of visual communication skills has received little attention. It is not discussed in the academic literature and the following quote suggests that it is given little attention in graduate education: "Most scientists were scarcely exposed to formal training in the use of visuals and it is our experience that students resort to learning by doing and imitating what they read and see, for better or for worse" (Desnoyers, 2011). (Luc Desnoyers is a retired biology professor who has been involved in the training of graduate students from different fields in science communication for more than 30 years).

Why this lack of attention? Perhaps limited competence in visual communication amongst scientists is not seen as a problem. An awareness that some visuals are poorly designed and therefore difficult to interpret may be seen as poor performance on the part of individual scientists rather than a generalized need to improve training in this area. Inversely, awareness that some visuals are exceptionally effective may be seen as a bit of impressive work, but not evidence that with training, more scientists could create visuals of this level of quality. And while scientists may be perfectly aware that people in other fields such as graphic design are creating more elegant visual representations, the idea that some of those skills could be acquired by scientists themselves may seem irrelevant – the visual communication traditions of science are distinct from those of graphic design. They have emerged from within science – developed by practicing scientists to meet the needs of practicing scientists. Scientists *do* have a history of utilizing the skills of scientific/technical illustrators, particularly in fields such as biology and medicine where there is a need to faithfully capture the appearance of specimens, and particularly for visuals used in textbooks where the demand for professional quality is higher and there is a budget to cover the expense. But this is somewhat peripheral to the day-to-day experience of most scientists. The bulk of visual communication between scientists relies on the visual communication skills of scientists themselves. The premise of this dissertation is that visual communication in science is sufficiently important to justify investing time and effort in better understanding the nature of competence in visual communication and the potential for enhancing it.

THE NATURE OF COMPETENCE IN VISUAL COMMUNICATION

Competence is defined as either the ability to perform, or the requisite skills and knowledge for performing. *Competence in visual communication*, then can be defined as the ability to create effective visuals or the skills and knowledge necessary for creating effective visuals. Effective visuals are, by definition, visuals that have the desired effects, or impacts. Figure 1 lays out these three components of competence in visual communication along with a fourth component, learning experiences, which refers to experiences that foster the desired skills and knowledge. This characterization of competence in visual communication will be used throughout this dissertation.

Figure 1: The components of ***competence in visual communication***

THE RESEARCH QUESTIONS

The research questions addressed by this dissertation correspond to these four components:

1. What are the desired impacts of science visuals?
2. What are the characteristics of an effective visual – a visual that will have these desired impacts?
3. What skills and knowledge enable an individual to produce an effective science visual?
4. What forms of learning experience develop these skills and this knowledge that constitute competence in visual communication for scientists?

   There are four sub-questions related to this:

   a. How are graduate science students currently learning to create visuals?
   b. Is their education giving them the skills they need?

c. Is instruction in visual communication valuable to science students?
d. How do science students respond to formal instruction using design pedagogy strategies?

WHY AN INFORMATION SCIENCE TOPIC

Contributions to the literature on information visualization do not generally come from Information Science (though there are significant exceptions – e.g. Chaoimei Chen, Katy Borner, Anselm Spoerri). The literature reviewed for this dissertation includes just a handful of writings from information scientists. However, as my colleagues and I argue (Ostergren, Hemsley, Belarde-Lewis, & Walker, 2011), Information Science is uniquely positioned to make contributions to this area. It offers an information-centric perspective which comes from a passion for facilitating encounters between people and the information they need, an appreciation for the value of structuring information to make it accessible, and an understanding of behaviors people engage in to clarify and satisfy their information needs. Information Science also offers a tradition of crossing disciplinary boundaries and blending disciplinary perspectives, which includes an appreciation for the validity of different approaches to research. This is reflected both in the varied disciplinary backgrounds of Information Scientists themselves and the nature of the field as a meta-field that can apply its knowledge to all disciplines. This openness is essential for this integrative scholarly work that brings together contributions from such profoundly different disciplines.

STRUCTURE OF THIS DISSERTATION

The overall structure of this dissertation is as follows. It begins with a description of current knowledge (chapter 2 & 3). This is followed by a description of the research methods (chapter 4), a detailed description of the findings (chapters 5-9) and an integrated summary of those findings (chapter 10). It concludes with a discussion of the contributions of this work and implications for practice and additional research (chapter 11).

The description of current knowledge begins with a characterization of the contents of three bodies of literature that were drawn from (chapter 2): the literature about the roles of visuals in science; the literature about what makes visuals effective; and the literature about the skills & knowledge and learning strategies for creating effective visuals which are used in the field of information design. Chapter 3 summarizes our current knowledge about vision and visual cognition, which is used to interpret findings presented in chapter 7.

Chapter 4 describes the data gathering and analysis process, which included an empirical study and a set of integrative literature reviews. The chapter begins with a description of the participants in the empirical study (a series of interviews and class observations), the procedures followed, and the resulting data. It then describes how *Thematic Analysis* was used to create a list of themes that faithfully reflect the data. This is followed by a description of the procedures followed for the two integrative literature reviews to produce a list of themes and concepts that could be combined with themes from the empirical study to create a conceptual framework.

The findings section (chapters 5-9) starts with the findings related to the sub-questions of research question #4 (i.e. how graduate students currently develop competence in visual communication, whether their education is giving them the skills they need, whether they feel that formal instruction in this area would be desirable and how they responded to design pedagogy strategies used in the course). The subsequent four chapters, 6-9, describe the findings related to the four major research questions. Each of these chapters begins with an orientation to the literature accessed followed by a detailed description of the themes that were identified in both the literature reviews and the empirical study.

The integrated summary of the findings (chapter 10) presents the conceptual framework built from the themes described in the preceding chapters.

The final chapter (chapter 11) briefly summarizes the dissertation, then describes the contributions and limitations of this work followed by recommendations for future research and for practice including a suggested curriculum and strategies for delivering that curriculum in the graduate school context.

The first three appendices list the publications included in the two literature reviews and the publications I drew from for insights into design and design education. The fourth appendix is the script for the interview.

CHAPTER 2: RELEVANT LITERATURE

Though the topic "how scientists acquire competence in visual communication" is not explicitly addressed in the published literature, there are several bodies of literature that inform this topic. In this chapter, I will provide a brief introduction and characterization of these bodies literature. Later in this dissertation, I will describe the results of an in-depth analysis of these bodies of literature.

These literatures can be clustered into the three groups. The first group, which I refer to as *Effective Visuals*, addresses the nature and value of visuals as a tool for communication. The second group, which I refer to as *Visuals in Science*, addresses the roles of visuals in science. The third group, which I refer to as *Design Expertise & Education*, addresses the acquisition of visual communication skills. I describe each of these in more detail below.

THE EFFECTIVE VISUALS LITERATURE

The *Effective Visuals* literature includes contributions from a variety of domains including educational psychology, cognitive psychology, and visual communication design. I identify it as a "body of literature" based on the fact that each contribution addresses the question of what makes visuals effective. However it is not a well-integrated or cohesive body of literature. As Levie points, "An aerial view of the picture research literature would look like a group of small topical islands with only a few connecting bridges in between" (Levie, 1987, p. 26). The contributions address topics as varied as the uses of color (Brewer, 1994a), the importance of domain-specific visual conventions

(Hoffmann, 1995) and the way we interpret spatial relationships between elements on a page (Tversky, 2005a). Even within a given topic, different fields take very different perspectives. For example, (Zacks & Tversky, 1999), (Cleveland & McGill, 1984) and (Rogowitz & Treinish, 2009) all discuss how to select an appropriate graph style for representing a set of data, but Zacks & Tversky, cognitive psychologists, focus on how well the choices align with the way we think about elements in the real world while Cleveland & McGill, statisticians, focuses on how different representations affect the speed and accuracy of interpretation and Rogowitz & Treinish, computer scientists, focus on how well different representations align with the nature of the data and the nature of the task. For this dissertation, I will be analyzing these varied contributions to find coherence within this diversity by identifying a set of themes related to *what makes visuals effective*.

THE VISUALS IN SCIENCE LITERATURE

The *Visuals in Science* literature includes writings about the roles visuals play in the scientific endeavor: how they enable scientists to work collaboratively; how they help scientists to understand complex concepts and complex data sets; and how they document knowledge in ways that enable others to build upon it. These writings include contributions from scientists themselves as well as academics who study the history of science, the philosophy of science and the sociology of science. In contrast to the *Effective Visuals* literature which focuses on individual viewers interacting with individual visuals, this literature considers viewers and visuals within the broader sociocultural and historical context, a context in which those viewers (scientists) are members of laboratory groups and of larger cohorts of fellow scientists, where the goals of visuals includes the need to establish credibility and make an argument for the acceptance and adoption of the new data or idea presented.

These contributions tend to fit into one of three categories: the role of visuals in interactions amongst scientists, the role of visuals in the evolution of disciplines as evidenced by changes over time, and the role of visuals in the scientific endeavor as a whole. An example of the first category is Robert Kozma et al.'s (Kozma, Chin, Russell, & Marx, 2000; Kozma & Russell, 2005) observations of differences between the ways chemists and chemistry students use visual representations while working in the laboratory. An example of the second category is Martin Rudwick's (1976) seminal work in which he describes the evolution of geology map conventions and the impact of historical realities such as mining practices and the presence of a scientifically-oriented leisure class. An example of the third is Bruno Latour's (1990) essay in which he lays out the profound implications of our ability to capture and consolidate ever-more numerous and varied scientific observations in forms that are easy to accurately reproduce and small enough to fit within our visual field. In contrast to the *Effective Visuals* literature, this is a relatively cohesive body of work; there is a clear sense of these authors building upon each others' ideas. The challenge in analyzing this literature for the purposes of this dissertation is to identify how these contributions give us a more complete picture of what it means for scientists to be competent visual communicators.

THE DESIGN EXPERTISE & EDUCATION LITERATURE

The third body of literature, *Design Expertise & Education*, includes writings by those who study design and design education. The field of Visual Communication Design (VCD) represents one of the few established traditions of teaching students to create effective visuals. As such, it is an important source of insight into how people learn to create visuals and the skills and knowledge they need to make them effective. In this dissertation, I will identify and compare these insights to the evidence from an empirical study which looks at the learning experiences science students have in graduate school and how they respond to pedagogical interventions aimed at helping them learn more.

VISUAL LITERACY LITERATURE

Before moving on, I want to acknowledge a body of literature that discusses the concept of *visual literacy* for science students. It addresses a concern amongst science educators that there has been insufficient focus on teaching students to understand and interpret visual representations (e.g. (Avgerinou & Pettersson, 2011), (Felten, 2008), (Trumbo, 2006)). Though clearly related to the topic of this dissertation, the focus of this research is on K-12 education and on the skills required to understand rather than produce visuals and therefore has relatively little to contribute to the current research questions.

THE GAP IN OUR KNOWLEDGE

The metaphor of a "gap" in our knowledge evokes an image of a knowledge landscape in which some areas are peppered with research contributions while others are sparse or unpopulated. I envision this research as filling in one of these sparse areas not by adding new dots to the landscape, but by drawing connections between existing dots in a sufficiently coherent way to create a mesh that covers these formerly empty regions.

CHAPTER 3: ADDITIONAL BACKGROUND KNOWLEDGE-VISION & VISUAL COGNITION

This chapter provides a high level overview of our knowledge of vision and visual cognition. This knowledge is drawn upon in chapter 7 to show how characteristics of effective visuals are aligned with the architecture of vision and visual cognition.

An important caveat is that virtually all of this information is theoretical and few if any of these theories are unchallenged. Though our knowledge of vision and visual cognition is extensive, it is far from complete.

Figure 2 shows a radically simplified rendition of the elements of vision and visual cognition. It includes three main components labeled *Visual Perception*, *Working Memory* and *Long-term Memory*. *Working Memory* is colored white to reflect the fact that this is the only aspect of visual processing that is available to conscious awareness. *Visual Perception* is colored dark gray in to reflect the fact that we are not, and cannot be, aware of the work our brain does to turn photo-receptor activation into meaningful input. *Long-term Memory* is split. The light gray portion represents knowledge that can be brought into conscious awareness. The dark gray portion represents forms of knowledge that are not accessible to conscious awareness. For example, we can bring to awareness a mental image of the structure of DNA, but we cannot bring into awareness the mechanism by which we pre-consciously match a given visual presentation with our knowledge of the structure of DNA.

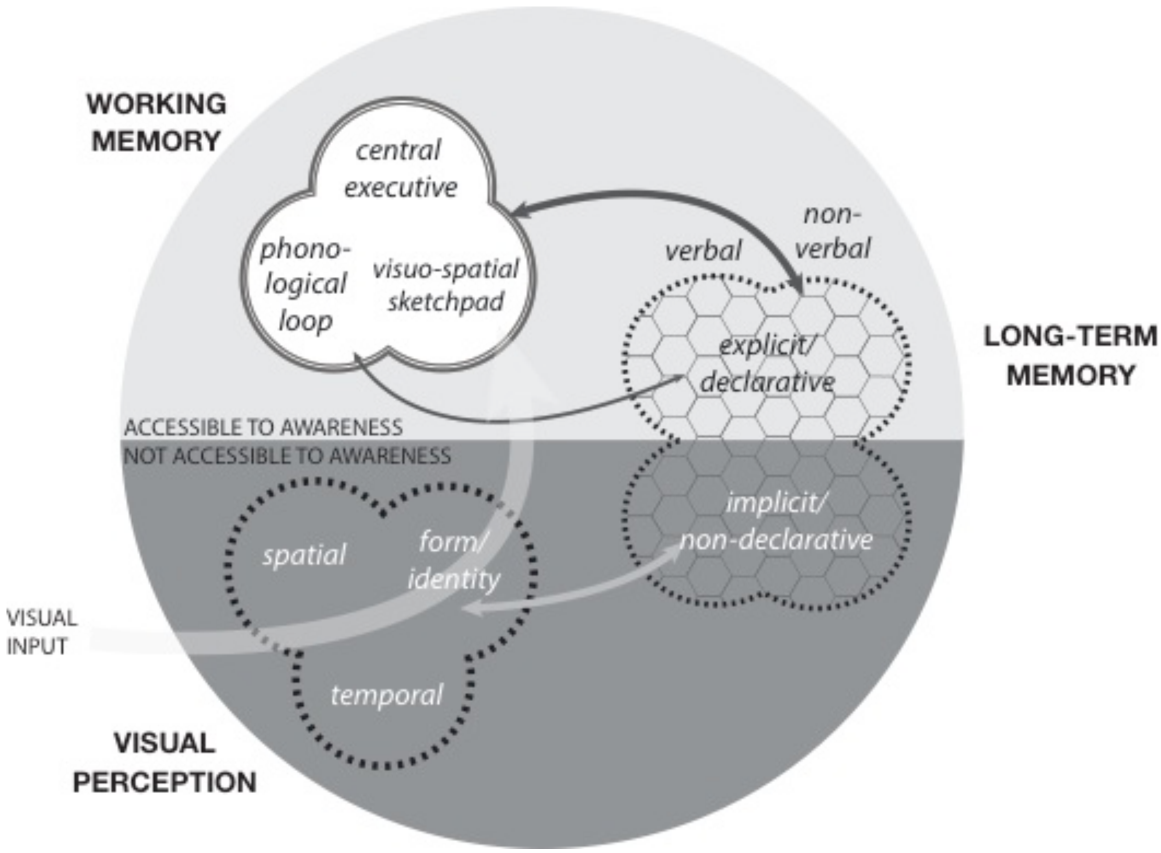
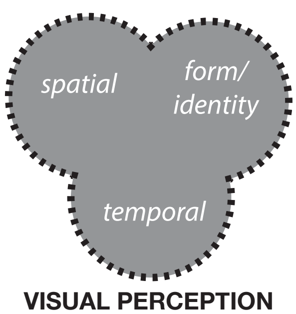


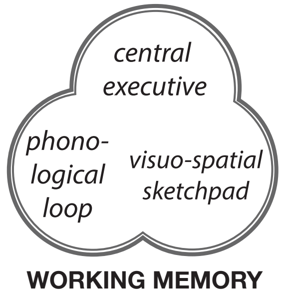
Figure 2: Elements of vision and visual cognition

VISUAL PERCEPTION



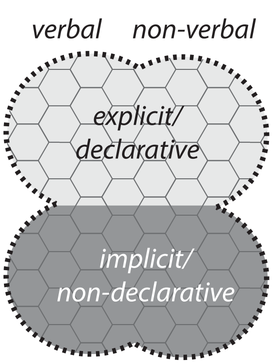
Visual Perception turns raw retinal data into meaningful information that is used to control movement and to inform us about the identity, position and motion of objects in the world (Hoffman, 2000). *Visual Perception* feels effortless yet the work involved occupies a significant portion of the cortex (Cavanagh, 2011; Ullman & Power, 1997), and it represents a sophisticated intelligence that is distinct from conscious cognition (Cavanagh, 2011; Rock, 1983; Ullman & Power, 1997). As the diagram indicates, visual perception is not a unitary concept—different neural pathways process different types of information (Ungerleider & Mishkin, 2000). The information from these different neural pathways is used for different purposes. One purpose is to provide information to parts of the brain that control muscles (e.g. to guide hand position while reaching for an object). Another purpose is to provide information for conscious processing in *Working Memory* (Milner & Goodale, 1995).

WORKING MEMORY



Working Memory is where information from *Visual Perception* and *Long-Term-Memory* are temporarily held for conscious processing (A. Baddeley, 2012; Kalyuga, 2006). Like *Visual Perception*, *Working Memory* is not unitary – it is divided into a *Phonological Loop* where verbal information is processed, a *Visuo-spatial Sketchpad* where nonverbal information is processed, and an *Executive Function*, which controls attention (A. Baddeley, 2012). One factor influencing attention is the affective response elicited by the object being viewed, which has implications for design (Adolphs, 2004; Fichtenholtz & LaBar, 2012). The *Visuo-spatial Sketchpad* is further divided into spatiotemporal, object identity, and place recognition components (A. D. Baddeley, 1999; Wood, 2011). A functionally important characteristic of working memory is that it is limited (indicated in the diagram by the double-outline in contrast to the other elements which have dashed outlines to suggest that they are theoretically unlimited). When overloaded, *Working Memory* cannot function effectively (Baddeley, 1999). One strategy the brain uses to avoid overloading working memory is to retain only core, essential portions of the information available from visual input needed for the current task (Chabris & Kosslyn, 2005; O'Regan, 1992). The fact that *Working Memory* is limited has implications for designing visuals, though is not necessarily a disadvantage from an information processing perspective since restricting the amount of information in *Working Memory* allows selective focus (Hasher, Lustig, & Zacks, 2007).

LONG-TERM MEMORY



Long-term Memory is where knowledge and skills are stored (Kalyuga, 2009). There are different theories about how this information is organized. A prominent one is the concept of schemas introduced in 1932 by Frederic Bartlett (Bartlett, 1932). Schemas are mental knowledge structures. We can have schemas at different levels of abstraction – e.g. a schema for "animals," a schema for "dogs" and a schema for "poodles." These various schemas are simultaneously intertwined and distinct. Schemas may include declarative knowledge like the types of food dogs eat, as well as other forms of knowledge such as skills that require practice to acquire, like the ability to read subtle aspects of a dog's body language. Memory involves both storing new knowledge and skills in schemas and retrieving those schemas when desired (Worthen & Hunt, 2010). Like *Visual Perception* and *Working Memory*, *Long-term Memory* is not a unitary entity – not only does it contain different types of information, some of which may be acquired through practice and inaccessible to conscious awareness, but it also appears to be divided into verbal and non-verbal stores (Paivio, 1991). These two systems are independent, but retrieving either verbal or non-verbal information about a concept can trigger retrieval of the associated information in the other store. This leads to the Dual Coding Theory which states that information will be more easily retrieved if it is stored in *both* verbal and non-verbal forms than if it is stored in only one form (Paivio, 1991). It is also fairly well-documented that visual information is more easily retrieved than verbal information – known as the Pictorial Superiority Effect (Paivio & Csapo, 1973). An important relationship between *Long Term Memory* and *Working Memory* is that *Working Memory* can process a limited number of "chunks" of information, and schemas are retrieved as "chunks." The more information that is contained in a schema—i.e. the more well-developed a schema is, the more total information can be held and processed in *Working Memory*. One major distinction between experts and novices is that experts having more well-developed schemas and can therefore process more information (Chi, 2006).

To summarize, the three major components involved in processing visual information are *Visual Perception*, *Working Memor*y and *Long-term Memory*. I will use this structure in chapter 7 to show how characteristics of effective visuals are aligned with this architecture of vision and visual cognition.

CHAPTER 4: RESEARCH DESIGN AND METHODOLOGY

To address the research questions presented in chapter 1, I conducted two complementary forms of research: an integrative literature review that identified themes related to the four aspects of developing competence in visual communication, and an empirical study with graduate-level science students that explored their experience of learning to create visuals and their thoughts about how their education supported this. In this chapter I describe the methods I used for conducting both forms of research and analyzing the results. The results of these analyses are presented in chapters 5-9: The first chapter presents findings from the empirical related to how the students in the study learned to create visuals. The subsequent four chapters each present findings related to one of the four areas of *competence in visual communication* (shown again in Figure 3). These chapters combine findings from both the integrative literature review and the empirical study. Chapter 10 brings together the findings described in chapters 6-9 in the form of a conceptual framework.

Figure 3: The components of *competence in visual communication*

RESEARCH COMPONENT I: EMPIRICAL STUDY OF GRADUATE-LEVEL SCIENTISTS

One goal of this research was to learn more about how graduate students currently learn to create visuals and to get their perspective on the value of explicit training. To address this goal, I gathered information from two sources: a series of interviews, and a collection of documents produced by students enrolled in a course on creating science graphics. The course and the data gathering procedures are described in detail below.

Course description

The course, an intensive 5-week summer offering, was taught by a cognitive scientist with input from a design professor. The pedagogical strategies included:

- *Formal lectures*: Students learned about cognitive design principles from lectures.
- *Learning-by-doing*: Students used their new knowledge plus feedback from the instructor and classmates to redesign visuals they had created prior to the course.
- *Guided design process experiences:* Students were guided through a design process, which involved creating parallel versions of their designs, giving and receiving critique, and creating consecutive versions of their designs.
- *Critique from an expert and peers*: Students learned to give and receive design critique in a group session led by a design instructor and in one-on-one peer sessions. The group session followed the traditional model in which each student stood in front of the group and described their designs, then received feedback from the instructor as well as their peers. For the peer sessions, each pair of students took turns giving feedback on each others' designs. Prior to these sessions, they had completed a form that provided structure for their comments. For example, they were first asked to "Walk your peer through the experience you had when you sat down with their presentation for the first time" in order to help their peer see what another viewer saw.
- *Prompts to reflect on learning:* The students were asked to maintain an online "portfolio" of their work which included copies of each version of their visuals, descriptions of their design goals, their own evaluation of its success, the feedback they received during critique, and the motivation behind their modifications. At the end of the course, they were asked to complete a self-evaluation form in which they described their most important learnings and insights, frustrations or disappointments.
- *Written feedback from the instructor:* Throughout the course, the students received written feedback from the instructor based upon their portfolios.

The course as a "probe"

The course acted as a "probe," meaning that it elicited comments and behaviors that provided insight into the students' state of knowledge (e.g. when students indicated that concepts conveyed in the course were new to them, it suggested that these concepts had not been part of the learning they had experienced thus far). It also elicited responses to the pedagogical strategies used in the course. The concept of a probe as a research tool was introduced by researchers in the field of human-computer interaction (HCI) who sought to understand the audiences they were designing for (Gaver, Dunne, & Pacenti, 1999). The concept has since been adopted in various forms and for various purposes (Boehner, Vertesi, Sengers, & Dourish, 2007). I use the term here to refer to an intervention in which the focus is not on the probe itself, but the responses it evokes (Hutchinson et al., 2003 is an example of this).

Influence of my participation in the course

Although I was not formally affiliated with the course, I was present at every course session and acted as a teaching assistant—answering students' questions, helping the instructor with small tasks and presenting lectures when she was gone. Because of this involvement with the course, it is possible that students' comments about the value of training in visual communication were influenced by their perception that it was, in some sense "my" course. I was present at all of the class sessions and assisted the teacher when needed. This included lecturing on two days when the teacher was absent. It is thus possible that my involvement in the course influenced the students' comments about the value of the course during their interviews, although I tried to minimize this by pointing out that this was not *my* course and that I was interested in their answers but not vested in them.

Participants

A total of 25 graduate-level science and engineering* students participated in various parts of this study. Figure 4 illustrates the breakdown: of the 15 students enrolled in the course, 14 agreed to make their course materials available for this study. 8 of these students also agree to participate in the interview. An additional 14 interview participants were recruited from science and engineering programs across the university through email announcements to representatives at each department.

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* This work focuses on science although it applies equally well to research engineers. I emphasize "science" rather than "science & engineering" throughout because there are visual traditions in engineering which are not emphasized in this work.

* For those viewing this without color, the first color scheme goes from saturated orange to

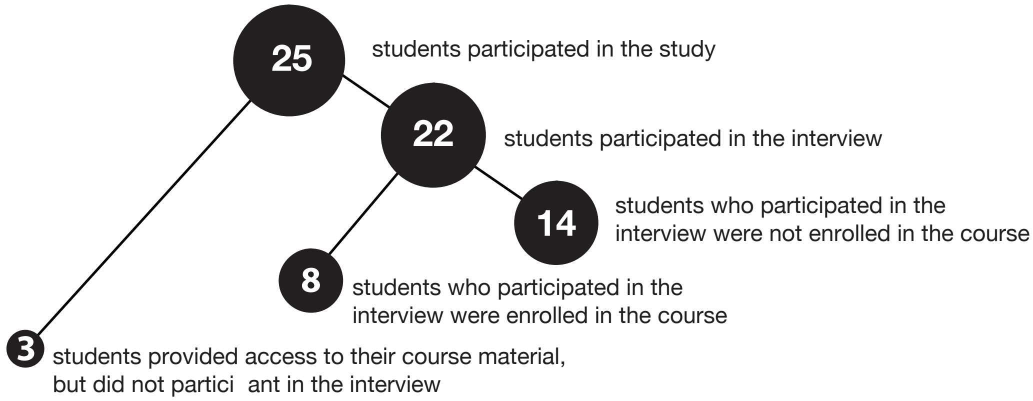


Figure 4: Breakdown of the 25 study participants

The 25 participants represent 13 departments in 4 schools or colleges, as shown in Figure 5.

College or School	Number of Participants	Department
College of Arts and Sciences	■ ■	Chemistry
	■ ■	Physics
	■	Biology
	■	Astronomy
College of the Environment	■ ■ ■	Atmospheric Sciences
	■	Earth and Science Sciences
	■	Aquatic and Fisheries Sciences
	■	Environmental and Forest Sciences
College of Engineering	■ ■ ■ ■	Computer Science
	■ ■	Civil and Environmental Engineering
	■	Mechanical Engineering
School of Medicine	■ ■	Rehabilitation Medicine
	■ ■	Physiology and Biophysics

Figure 5: Colleges and departments represented by the 25 participants

Interview procedure

The interview was designed to elicit information about how participants learned to create visuals and their thoughts about the value and purpose of those visuals. The full interview script is included as Appendix 4.

An interview was conducted twice with each participant – once during the two weeks before the course began, and once during the two weeks after the course ended. The main benefit of interviewing each participant twice was the opportunity it afforded to see responses with and without the influence of the probe (the course). The purpose of including participants who were *not* enrolled in the course was to have a larger and therefore more representative sample, and to provide an opportunity to see whether the students who had chosen to take the course were unusual – whether their experiences learning to create visuals were substantially different from students who had not chosen to do so.

Course materials data

As shown in Figure 4, eleven participants made their course-work available for this research project. This coursework consisted of three types of material: a *Course portfolio* in which students described their thoughts and processes as they redesigned visuals they had created in the past based upon what they learned in the course (a screenshot is shown in Figure 6 and an excerpt in Figure 7); *Peer feedback* forms in which students documented feedback for two assigned peers (an excerpt is shown in Figure 8); and *Course reflection* forms in which students made comments about the value of the content and pedagogical strategies of the course (an excerpt is shown in Figure 9).

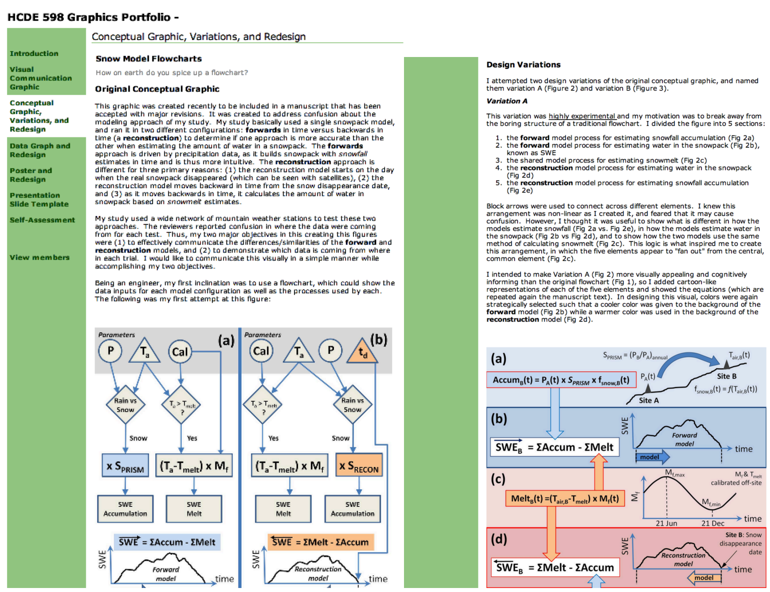


Figure 6: Screenshots of a student's online portfolio

Initial Redesign

After receiving feedback, I decided that I would like to make a redesigned graphic that represents a hybrid between Variations A and B. I received the suggestion to make a "triangle-like" arrangement, with a simple mountain scene (like Fig 2a) at the top and the two models side by side below that mountain scene. I also received the recommendation to make the next redesign into a black & white image, and add color only when necessary. With this (and the previous) feedback in mind, I created the first redesign, shown below in Figure 4.

Figure 7: Excerpt from student portfolio

Reflection Insights

Now read carefully what your peer has written in each tab. What visual or informational problems has your peer been struggling with? Have the redesigns addressed the concerns? Can you provide any further solutions? Are these the same problems that you've encountered in your own work? What is the same and what is different?

Looking at all the pieces of his portfolio, it seems like the main issues that Brian is wrestling with are complexity and information overload. This presents itself in every aspect of his work. For his conceptual graphic, he is trying to present winds going all different directions and is using both a 2D and 3D graph to accomplish that. Similarly, his data graph is attempting to express two main points/conclusions: showing how temperature and elevation interact and comparing how different atmospheric dynamics impact that interaction. Finally, the main challenge with his poster was to reduce the visual overload and density of information presented on the poster to reduce the load on the viewer. The slide design is the only place this wasn't an issue.

Figure 8: Excerpt from a peer feedback form

	While viewing/making your own graphics	During the critique or peer assessments
A-ha moments (Moments of realization, of all of a sudden understanding something)	**Chunking the experimental categories on the data graph! Why did I not think of that?**	**People telling me I could desaturate the circles representing others' experiments in the data graph. I guess I didn't think of it because I was Getting Away From Saturation. I can get overly literal like that.**
Frustrating moments	**Wrestling with my desire for colors I find appealing vs. more usable colors. I went with the white background version of my poster, but it messes with my self-image a little to have such a normal-looking poster.**	**Trying to tell someone that their graphic was not conceptual. Failing. We all tried to say it, but maybe we were too nice.**
Moments of satisfaction	**I made that lossy arrow work in the visual communication graphic. The first version was just not what I wanted. I think I could still improve it, but this is much more like it.**	**Karen said my conceptual graphic redesign #1 looked like it was made by a designer, and someone said I should put it on a t-shirt. I liked it, but I didn't realize it had that kind of appeal.**

Figure 9: Excerpt from a student course assessment form

Analysis

The interview and coursework data was analyzed using Thematic Analysis as described by Braun & Clarke (2006). The phases of this approach consist of:

- Familiarizing yourself with your data
- Generating initial codes
- Searching for themes
- Reviewing themes
- Defining and naming themes
- Producing the report

The first phase, *familiarizing yourself with the data*, consists of reading and re-reading the transcripts, summarizing and making comments as a way of actively engaging with the content to become familiar with it.

The second phase, *generating initial codes*, involves tagging segments of text that address a single concept. For example, the segment below was tagged "*learn the best way to learn is by seeing bad presentations":*

> I have seen bad presentations, I think is the best way to learn it. Like literally, I was just listening to a cartoon making fun of the 'dos and don'ts', they say these are the 'dos' but they kind of flip them from what they should be, such that the cartoon is kind of mocking Power Point and, I have seen a presentation at the conference in Orlando in February and literally there was no white, the joke was like 'if you see white, fill it', like that's what you shouldn't do. There was like, it was unbelievable, it was so bad and people always joke about that and I actually saw one. —Participant #9 (physicist), first interview

This segment was judged to reflect a single concept because most of the text is an expansion on the idea of learning about creating visuals by seeing bad examples.

The third phase, *searching for themes*, involves sorting the codes to identify common themes and sub-themes. The example below shows how concepts in the interview comments were grouped into two sub-themes and one main theme:

THEME: LEARNING STRATEGIES/METHODS

- Sub-theme: Learning by observation
    - Seeing bad presentations
    - Seeing others' figures
    - Observing what others have done
- Sub-theme: Learning by trial and error
    - Trial and error – playing around with shapes and shading
    - Trail and error based on feedback from advisor, students etc.

The fourth phase, *reviewing themes*, involves reviewing the codes to be sure they are coherent and distinctive, and then re-reading the transcripts to confirm that they accurately represent the data.

The fifth phase, *defining and naming themes*, involves defining each theme to capture its essence and identify its relevance to the research question.

The sixth phase, *producing the report*, involves writing the narrative around the themes and finding extracts that are accurate and compelling representations of each theme.

For this project, this final phase of the data analysis also included a process of comparing and contrasting the themes from the data with themes from the integrative literature reviews. This is reflected in the findings chapters (chapter 6-9) in which themes from the literature are aligned with themes from the empirical study.

RESEARCH COMPONENT II: INTEGRATIVE REVIEW OF THE LITERATURE

For each of the four research questions, literatures from multiple disciplines were brought together and analyzed through the lens of that question. For two of the research questions, "What skills and knowledge enable an individual to produce an effective science visual?" and "What forms of learning experience develop these skills and this knowledge that constitute competence in visual communication for scientists?" this process was reasonably straightforward because the number of contributions was manageably small. However, for the other two research questions, "What are the characteristics of a visual produced by a competent individual (a visual that will have the desired impacts)?" and "What are the desired impacts of science visuals?" the relevant bodies of literature were extensive and unwieldy. The strategy used to analyze them is referred to as an Integrative Literature Review. "The *integrative literature review* is a form of research that reviews, critiques, and synthesizes representative literature on a topic in an integrated way such that new frameworks and perspectives on the topic are generated" (Torraco, 2005, p. 356). It involves following a pre-defined process for identifying the literature, analyzing each contribution, and synthesizing the analyses to identify new insights.

Review procedures

The procedures I followed are based on those described by Torroco (2005) and by Whittemore and Knafl (Whittemore & Knafl, 2005). These procedures included defining the following five concepts for the purposes of the review:

Conceptual structuring

The reviews were guided by a specific point of view about these topics: an orientation toward the specific research questions.

Review Purpose

The purpose of the reviews was to identify the desired outcomes of science visuals and qualities that make those visuals effective.

How the literature was identified

In the standard integrative literature review process, the documents to be analyzed are identified through a systematic search of electronic databases using a consistent set of search terms. The purpose of using a systematic search strategy is to ensure that the collection of documents retrieved is inclusive and unbiased. Unfortunately, a systematic search was not feasible in this case – the literatures this review brings together are difficult to capture with keyword searching. This is partly due to a lack of unique and consistent vocabulary (e.g. searches on terms like visual communication," "visual representation," or "science visuals" bring up a rich array of results, few of which are highly relevant), and partly due to the fact that the unifying concepts that bring these contributions together are generally at a more abstract level than the language used to describe them in bibliographic databases (e.g. an article may talk about how visuals facilitate communication by acting as boundary objects, but will not refer to this as a form of impact or an outcome of a visual). As a result, finding the relevant literature in this area was an idiosyncratic process of identifying key documents through exploratory searching, and then following the citation trail forward and backward to discover related works, making numerous judgment calls along the way about which documents were worth pursuing. Codifying this process for replication is not practical or meaningful. As a result, the literature identified for this analysis reflects the diligent efforts of one individual researcher undertaken with an overtly multi-disciplinary bias—an active intent to include multiple perspectives. One aspect of this idiosyncratic process that can be made transparent is the list of major factors that influenced the decision to include or exclude a given reference from consideration:

Criteria for inclusion

- The article refers to any form of visual used in science communication
- The article refers to ways in which visuals differ from text in terms of how they communicate information
- The article refers to ways in which visuals supplement verbal forms of communication
- The article refers to how human visual perception and cognition resources work to process informative visuals
- The article refers to developing skills or knowledge for creating informative visuals
- The article refers to characteristics which make visuals more or less effective
- The article refers to how people learn from visuals

Criteria for Exclusion:

- The article refers only to automated imagery (e.g., photos, x-rays) without reference to modifying that imagery (e.g. with labeling or cropping) to make it informative
- The article refers to imagery/visuals for persuasion or advertising rather than education

- The article refers to K-12 education only. (The developmental differences and level of science being conveyed tend to make the contributions of this research difficult to apply to professional communication)
- The article refers to an algorithm for generating visuals rather than the visual itself
- The article focuses only on artistic (as opposed to informational) aspects of visuals

Analysis

I followed the data analysis process described by Whittemore & Knafl (Whittemore & Knafl, 2005). The steps in this process include data reduction, data display, data comparison, conclusion drawing, and verification.

Data reduction. In my initial attempt at reducing the information to a form that facilitated analysis, I created a series of categories based upon the themes from the interview and course data. I then began applying these categories to each document. This approach was inspired by the framework created for a Systematic review by Šmite, Wohlin, Gorshek & Feldt (2010). I knew that this process would be challenging, given that the widely varying types of documents, and knew that some elements of the framework would not apply to every document, but my expectation was that this would tease out clusters of documents that shared common characteristics (e.g. empirical versus theoretical studies). I found fairly quickly that the degree of variation was so great that this approach was not successful in identifying meaningful clusters.

My next approach was to sort and resort the documents based on similarity in content (whether by visual genre or discipline or experimental approach). With each sorting iteration, I spent more time with each document to develop a better understanding of its contribution – sometimes ultimately rejecting the document as insufficiently relevant. This approach was successful in identifying major groupings that were generally distinctive (although occasionally I had documents that could fit in more than one group). Throughout this process I kept notes about each document and at this point, I condensed my notes first into 1-2 sentence summaries and ultimately into phrases. At this level of data reduction I was able to grasp the range of topics and identify sub-clusters. Once sub-clusters were identified, I went back and filled in more detail in a process that both gave me a richer description of each cluster and helped me identify and correct any over-generalization that had taken place during the process of reduction.

Data display & data comparison. At this point, I looked for ways to visualize the data to get a sense of its scope and character. The results are the displays of author domains, subject domains and publications dates shown in chapters four and five.

Conclusion drawing and verification. Wittemore & Knafl (2005) describe this as the phase in which analysis moves from description to higher levels of abstraction and generalization. The patterns, themes and relationships identified in the previous step are analyzed for more general patterns within subgroups and then across subgroups. Torraco (2005) calls this final step *Synthesizing the literature*. He describes 4 ways in which new ideas can be synthesized from an integrative literature review: a research agenda, a taxonomy, an alternative model or conceptual framework, and meta-theory.

For this work, I have created a conceptual framework. The goals of this framework are:

- To stimulate engagement with this topic area by making it more accessible
- To elevate awareness of factors contributing to the development of visual competence
- To clarify the nature of competence in visual communication
- To make it easier to identify gaps and therefore stimulate new research
- To help to determine how new contributions relate to existing work

TRUSTWORTHINESS IN THIS WORK

Finally, I address issues relating to trustworthiness that have not been addressed by the above description of the research and analysis methods. The ideas are based on Andrew Shenton's work summarizing strategies for ensuring trustworthiness in qualitative research projects (Shenton, 2004).

The work of this dissertation is highly interpretive. The analysis methodology I chose is intended to ensure that the interpretation was solidly grounded in the data itself and that biases in my impressions were tempered by constant re-evaluation provoked by repeatedly returning to the data for verification. I also sought peer scrutiny; I had extensive conversations about my interpretations with my research colleague Dr. Yeechi Chen, a physicist, and additional conversations with the Dr. Kieran O'Mahoney, educational psychologist, and design professor Karen Cheng.

Experience and background

The background I bring to this interpretive work includes experience with learning and teaching visual communication in several settings; I have taken (or acted as a teaching assistant for) courses in visual communication taught by cognitive scientists, professional designers and computer scientists. I taught a course on visual communication using the knowledge and skill I gained from those different forms of instruction along with my observations of how they influenced my own design work in order to inform my teaching.

Although my own graduate school experience has been in the social sciences, the science world is not unfamiliar to me. For 13 years I worked with research scientists and natural resource managers in the National Park Service while developing and managing a bibliography project. I read and summarized thousands of publications and attended conferences where park-based scientific research was presented. That experience gave me some context for understanding the work and experience of the graduate students I interviewed for this dissertation. I also became familiar with academic science culture while working on a research project under the supervision of Marco Rolandi, a Materials Science Engineer, and participating in weekly lab meetings during which his students presented the results of their research.

CHAPTER 5: HOW SCIENTISTS LEARN TO CREATE VISUALS

The fourth research question, "What forms of learning experience develop the skills and knowledge that constitute competence in visual communication for scientists?," has four sub-questions that relate to how graduate-level science students *actually* develop competence in visual communication (as opposed to how they theoretically or ideally *should* develop this form of competence). The findings related to these sub-questions are presented here because they provide useful background for contextualizing the additional findings presented in the following four chapters. Since the literature does not discuss how graduate students actively develop competence in visual communication, these findings are exclusively from the empirical study—the interviews with graduate-level science students, and in particular their descriptions of how their educational experience has helped them develop visual communication skills. The chapter is structured around the four sub-questions, namely:

a. How are graduate science students currently learning to create visuals?
b. Is their education giving them the skills they need?
c. Is instruction in visual communication valuable to science students?
d. How do science students respond to formal instruction using design pedagogy strategies?

QUESTION A: HOW ARE GRADUATE SCIENCE STUDENTS CURRENTLY LEARNING TO CREATE VISUALS?

The answer to this question for the 22 graduate students interviewed for this research can be summarized as follows: In general, they figured out how to do so through their own initiative, in an environment in which:

- They had extensive exposure to visuals
- They received feedback from peers and advisors
- They frequently came in contact with the audience for their visuals

All of the 22 graduate students interviewed said they created visuals on a regular basis, although their experiences varied experiences in terms of the types of visuals they created, the software they used, the nature of the audience they created them for. The common themes in their comments are listed in Figure 10. The most prominent themes were that they figured out how to create visuals on their own with feedback from peers and advisors. The following excerpt is representative (brackets indicate words that were difficult to hear clearly):

> Just over time by doing it again and again. It's...I mean there are no formal trainings. So for now, it's mostly by doing it again and again. People giving you feedback that this could be good, this could not be good...[try] this, delete this...and then looking at presentations of other people, like other researchers who come and give presentations who have more experience. Looking at them, picking up stuff from there. So it's mostly self-learning [hit-and-try] kind of, that kind of thing. —Participant #16 (Chemical Biology), second interview

Types of learning

Learning Strategy	Number of Participants (Total = 22)
Figured it out independently	17
Received feedback	12
Emulated others	7
Undergraduate course	6
Work experience	5
High school course	4
Minor training experience	4
Guidance from peers	4
Guidance from professors	4

Figure 10: Themes related to how participants learned to create visuals and the number of participants who made comments relate to that theme.

Although most (17/22) participants said they felt they had figured it out on their own, they also mentioned learning from undergraduate instruction, from prior work experience, high school art courses, and minor training experiences in graduate school (a workshop or presentation). All of the students who mentioned undergraduate instruction were referring to learning to make data plots. Several said the software they learned for this purpose was not the software they use for their current research. The following quote is typical:

> In undergrad I would mostly have used, uh, Kaleidograph, which is kind of meant for Macs and works terribly on PCs and it, it's kind of that really like old pixelly kind of program and I don't know if it ever got updated and there were some like Mathematica and Origin around for computing. Um, and I think those work well for physics, but when you switch to earth science, Matlab is just seems to be the tool everybody's using and so I just started using that. —Participant #22 (Earth & Space Sciences), second interview

Those who mentioned high school art classes generally did so in response to being asked whether they had been exposed to visual design concepts. Below is one such response:

> I'm recalling where did I learn some of this stuff. And I was in high school. In my arts class. We had to do like these, banners or something like that and that's when I was introduced to some of the concepts that I'm talking about now. (…) Yeah, and now that you make me think about it I remember like the combinations of colors that work better or...yeah, that kind of thing. —Participant #20 (Wildlife Sciences), first interview

One individual came to graduate school with extensive art training which he felt was valuable in a number of ways:

> …and I have noticed a lot, like my...I get a lot of really great feedback on my presentations. And there's times when like I really have very little new science to present, but my presentations look great and people are like 'oh that was a great presentation' and I'm like 'okay, great, I thought I was going to fail miserably, but all of you are happy so...in that sense it's been good. —Participant #4 (Chemistry), first interview

Five participants mentioned professional experience that had been helpful because it gave them additional experience in creating visuals:

> Before I came to grad school I worked for a engineering firm for a few years, and we made a lot of slides for clients explaining what it was we were designing, and why we were making the decisions we were making, and so I guess I learned a fair amount about making sort of clear graphic slides in PowerPoint again based on sort of trial and error with what worked in a meeting setting. —Participant #12 (Civil Engineering), first interview

Only three of the 22 participants recalled an experience in graduate school that was explicitly intended to help them improve their visual communication design skills. One of these was a single lecture on preparing effective slides; another was a single lab group meeting during which each member shared something they had learned about creating good visuals; the third was a seminar course on communicating science that included visual communication.

QUESTION B: IS THEIR EDUCATION GIVING THEM THE SKILLS THEY NEED?

When the students were asked in the interview whether their education had given them the skills and knowledge they need to create effective visuals, they said "both yes and no." "No" because they had been given very little formal instruction, but "yes" because they had, indeed, learned to create visuals, and there were ways in which their education had provided them with what they needed through exposure, support, and opportunity.

> I feel like I guess it's kind of teased out the need to that… it's brought out the need to have that skill, if we want to call it that, but hasn't directly provided the tools to do it. —Participant #3 (Rehabilitation Medicine), first interview

Specific ways in which they felt their graduate experience had helped them included: giving them frequent exposure to science visuals in the journal articles they read and the presentations they attended; giving them the incentive to learn by presenting them with the need to analyze their own data, to communicate with their lab-mates or to present their results in lab meetings or conferences; providing them with feedback as part of the general culture of giving and receiving critical feedback.

Some said they would have liked to receive formal training, but two pointed out that learning to figure things out on their own was typical in graduate school:

> So it's been a really interesting...I kind of had to teach myself a lot…So...but I mean, you're always teaching yourself something in grad school. —Participant #5 (astronomy), second interview

On a final note, though there were strong common themes, there were differences in the experiences of the participants as well. Some felt that their advisors and lab-mates considered passable visuals sufficient while others felt their lab culture supported them in investing time to make a truly effective visual.

QUESTION C: IS INSTRUCTION IN VISUAL COMMUNICATION VALUABLE TO SCIENCE STUDENTS?

When the students were asked in the interview how valuable is to teach students to create visuals (rather than letting them figure it out on their own) they gave a range of responses. As indicated in Figure 11, fifteen participants, including some who had registered for the course, were unsure about what formal training would look like. Eight participants said they liked the idea of having some formal training, particularly to get past the steep learning curve involved in learning new software.

Others felt that formal instruction would be either unnecessary or even counter-productive. Of the 7 participants who made comments strongly in support of formal teaching, 6 had completed the course. The seventh was the student who had previously taken a seminar on science communication. (As mentioned in chapter 4, these response may have been influence by the perception that I would be sensitive to criticism about the course since I was involved, if only as an assistant.)

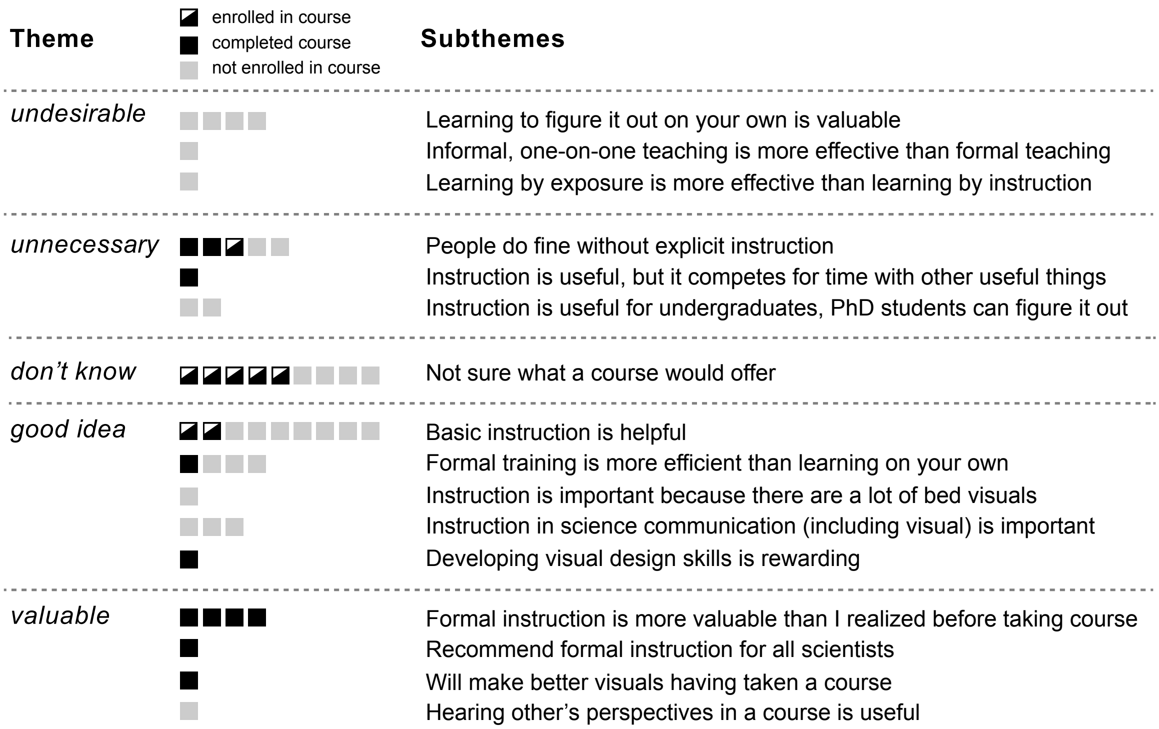


Figure 11: The value of teaching students to create visuals indicating which comments were made before the course, after the course, or by participants who had not enrolled in the course.

Figure 6 shows the scores students assigned when asked to rank the value of teaching scientists to create visuals on a scale of 1 to 5. Responses ranged from 2 to 5.

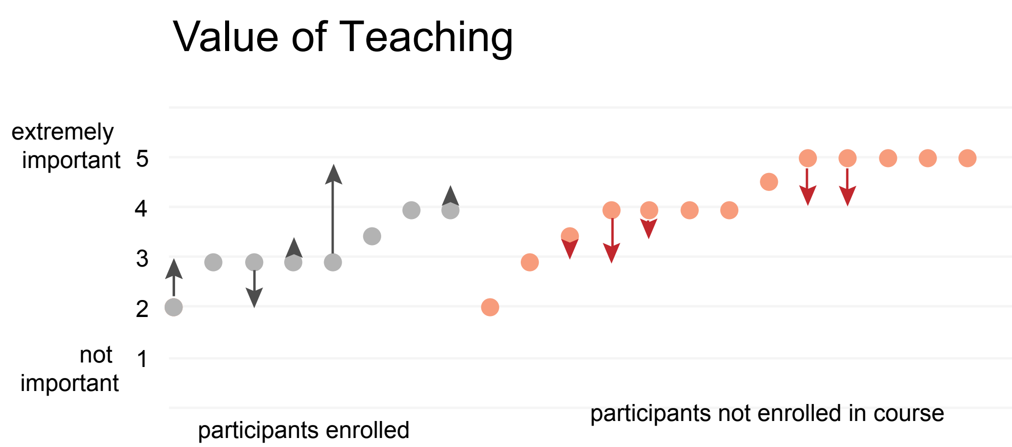


Figure 12: The circles indicate the scores participants chose in their first interview. The arrows point to the scores they chose in their second interview

Without making any claims to statistical significance, it is interesting to note the differences between the first and second interviews. Those who had *not* taken the course either kept the same score or ranked it even lower (less valuable) during the second interview. Those who *had* taken the course either kept the same score or ranked it higher (with one exception), during the second interview. Of the five participants who gave lower scores in their second interview, two said they had done fine without having formal training, and two said that while a course would be valuable for undergraduates, graduate students should be capable of figuring it out by themselves. Those who gave higher scores after taking the class said the class had been more effective than they had anticipated.

QUESTION D: HOW DO SCIENCE STUDENTS RESPOND TO FORMAL INSTRUCTION USING DESIGN PEDAGOGY STRATEGIES?

The students' response to the pedagogical strategies employed in the summer course gives additional insight into their prior knowledge and training as well as insight into the potential for using these strategies to help science students learn to create visuals. As described in chapter 4, the course was taught by a cognitive scientist who worked with a design professor to integrate traditional design education strategies. It incorporated experiential learning through assignments that required students to use design strategies such as making multiple iterations, and receiving and giving critique. The critique experiences consisted of two one-on-one peer feedback sessions and a group session led by a design professor in which each student described their work and received feedback from their peers and the instructor.

During the second set of interviews, all 8 of the interview participants who had taken the course volunteered comments about what the course had taught them at some point in the course of the interview. The themes in these comments are summarized in Figure 13.

Knowledge Theme	**Number of Participants (Total = 8)**	
Strategies for reducing complexity	6	■■■■■■
Design awareness	5	■■■■■
Design process	4	■■■■
Value of critique	4	■■■■
Self-awareness	3	■■■
Basis for future learning	2	■■
Design skill	1	■

Figure 13: Self-reported skills and knowledge acquired from design course

The most prominent theme (mentioned by 6 of the 8 students) was that the course had taught them *strategies for reducing complexity*. The following quote is representative:

> Um, I think in taking this course, especially, a baseline understanding of some human psychology is a useful skill to have. I have never really been exposed, I have never taken a course in psychology or anything like that, but just learning some very basic principles of things like, uh like the grouping theories and things like that where, ... or just even, I think something that was really revealing to me was the memory limitations that we have. Um, I found myself very guilty through this course of trying to put way too much information to burden the viewer. So reducing that or finding ways of grouping information to make it more palatable. —Participant #10 (Civil Engineering), second interview

Five of the participants said that the course helped them develop *design awareness* — a heightened sensitivity to the realm of design and to the process of designing visuals.

> ...it sort of helped refine a sense of design. —Participant #8 (Computer Science and Engineering), second interview

The remaining themes are less focused on the characteristics of the visuals themselves than on the process of design. Four participants referred to the value of learning about strategies related to the design process.

> I think that was a really valuable thing to force iterations…It starts out as kind of a yeah, really forced thing, but then sometimes like 'oh, I really like this part.' So I think it is really crucial. —Participant #8 (Computer Science & Engineering), second interview.

Four participants referred to learning the value of getting feedback from their peers during critique.

> …it was sort of an eye-opening moment to see, you know, other intelligent people who, I mean I would think otherwise would be able to sit down and figure out what I'm trying to say, to see them sort of struggle or to not really understand what's going on. Um, so that was, yeah, that was, um, I think I have kind of gotten sold on sort of having this intentional feedback. —Participant #10 (Civil Engineering), second interview.

Finally, three students said the course had helped them develop insight into their own skills and limitations as designers:

> I think being critical of your own design work is an important part of this process. A lot of my stuff was too busy, but I was too attached to it. —Participant #10 (Civil Engineering), second interview

HOW THIS OVERVIEW RELATES TO THE FOLLOWING CHAPTERS

This overview is intended to provide a snapshot of the setting in which scientists develop visual communication skills, and their perspective on the experience of developing those skills. It creates a context for the additional findings, from both the empirical study and the integrative literature review which are presented in next four chapters. Each of these four chapters addresses one of the four aspects of competence in visual communication presented in chapter 1 (learning experiences, skills & knowledge, characteristics of effective visuals and impacts of science visuals).

CHAPTER 6: WHAT ARE THE DESIRED IMPACTS OF SCIENCE VISUALS?

In this chapter, the first of four chapters presenting the findings related to each of the research questions, I present the findings related to the question "What are the desired impacts of science visuals?" These findings come primarily from an integrative literature review of the *Visuals in Science* literature. As mentioned in chapter 2, this literature includes writings about the roles visuals play in the scientific endeavor: how they enable scientists to work collaboratively; how they help scientists to understand complex data sets; and how they document knowledge in ways that enable others to build upon it.

Literature reviewed

The initial search for documents related to the impacts of visuals in science produced several hundred results, which were narrowed to a subset of 92 based on the inclusion/exclusion criteria listed in chapter 4. These documents are listed in Appendix 1.

The authors of these publications come from 14 disciplines (shown in Figure 14). They include philosophers, educators, psychologists, historians, scientists and more. Contributions from the three disciplines shown in the center: philosophy, history and sociology, are most central to the topic – they explore questions such as "How do visuals facilitate scientific communication in ways that differ from words?," "How do scientists use visuals in their day-to-day activities in the laboratory?" and

"How did visual conventions evolve to meet the needs of scientists?" Contributions from fields such as psychology and education contribute more indirectly, mostly through their efforts to understand impacts on individual viewers, asking questions such as "Why do science students struggle to understand visuals?" and "How does the choice of visual representation affect students' conceptualization of a scientific idea?" The research methodologies used in these documents are varied. They include laboratory experiments, field observations, and analysis of historical documents. They analyze visuals at every level, from individual case studies to entire visual genres and entire scientific domains, and address impacts on various aspects of scientific undertakings including the diffusion of theories, the impact in specific settings, and in the minds of viewers.

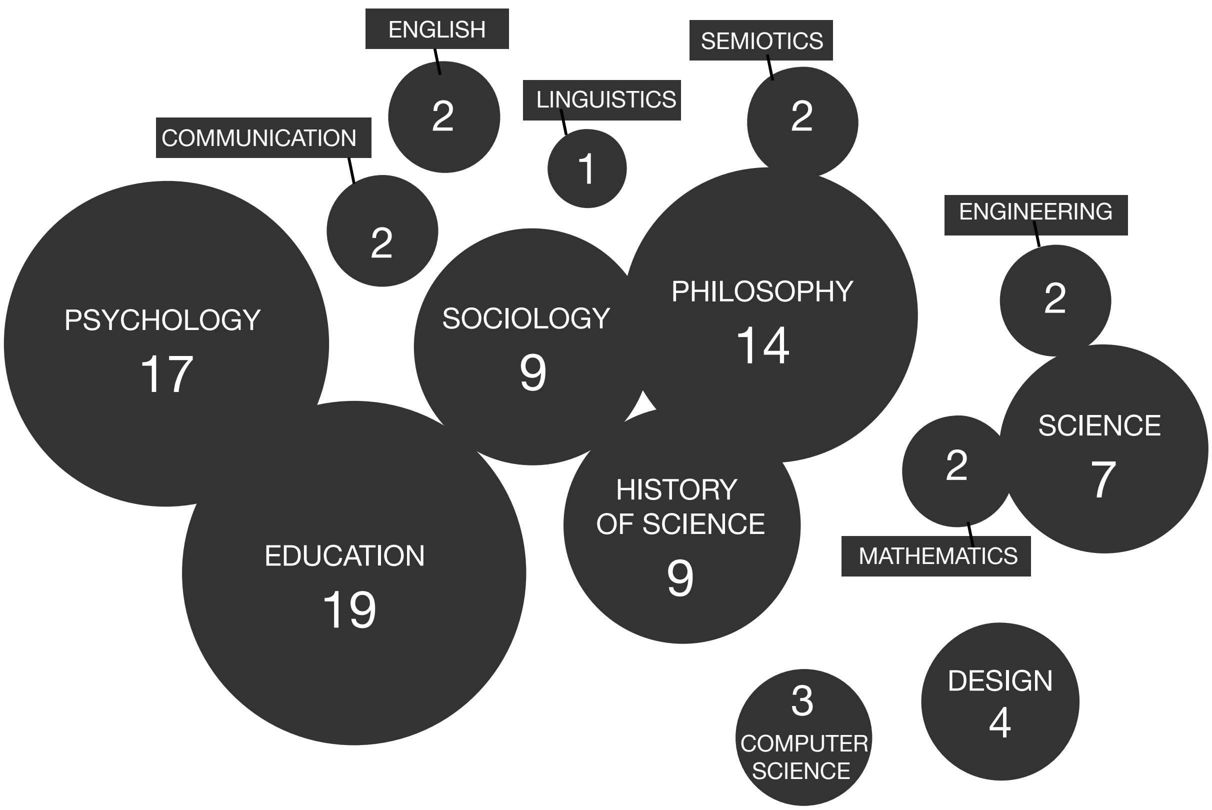


Figure 14: The 14 disciplines represented by the authors of the 92 publications included in this review (this accounting is accurate in broad strokes, although it is not always possible to pinpoint an author's discipline). The size of each bubble corresponds to the number of authors and the degree of overlap between bubbles roughly corresponds to degree of overlap in content within the bodies of literature produced by authors from these disciplines

Half of these documents were published within the last 10 years (as shown in Figure 15), but there are notable contributions from as far back as 1937—a review of the history of statistical graphics by mathematician Howard Funkhouser (1937)—and 1970—a fascinating book by neuropsychologist Richard Gregory with a insightful chapter entitled *Seeing how things work* which analyzes the ways we infer meaning about mechanical and electronic systems through drawings (Gregory, 1970).

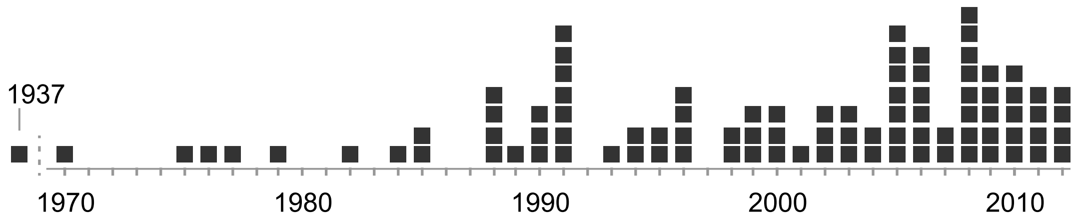


Figure 15: Publication dates of the 90 publications included in this review

The scientific and technical disciplines addressed by the 90 articles in this review are represented in Figure 16 (The hierarchical division of science disciplines is taken from a 2009 report by the National Science Foundation entitled ***Characteristics of Doctoral Scientists and Engineers in the United States: 2006*** (National Science Foundation Division of Science Resources Statistics, 2009)). Over half of the publications talk about science generally. Another third refer to specific scientific disciplines and include both case studies about a single visual or set of visuals (such as the drawings Linus Pauling used in an seminal article on the importance of the shape of molecules (Cambrosio, Jacobi, & Keating, 2005)), and the use of visuals in that discipline in general (an example being the article by David Knight who chronicles the development of illustrations accompanying articles on chemistry from portraits of chemists and illustrations of experimental equipment to early representations of molecules(Knight, 1996)). A handful of documents are specific to engineering, but have relevance for science as well. Some documents do not mention specific disciplines but are included because they refer to visual genres commonly used by scientists such as statistical graphs.

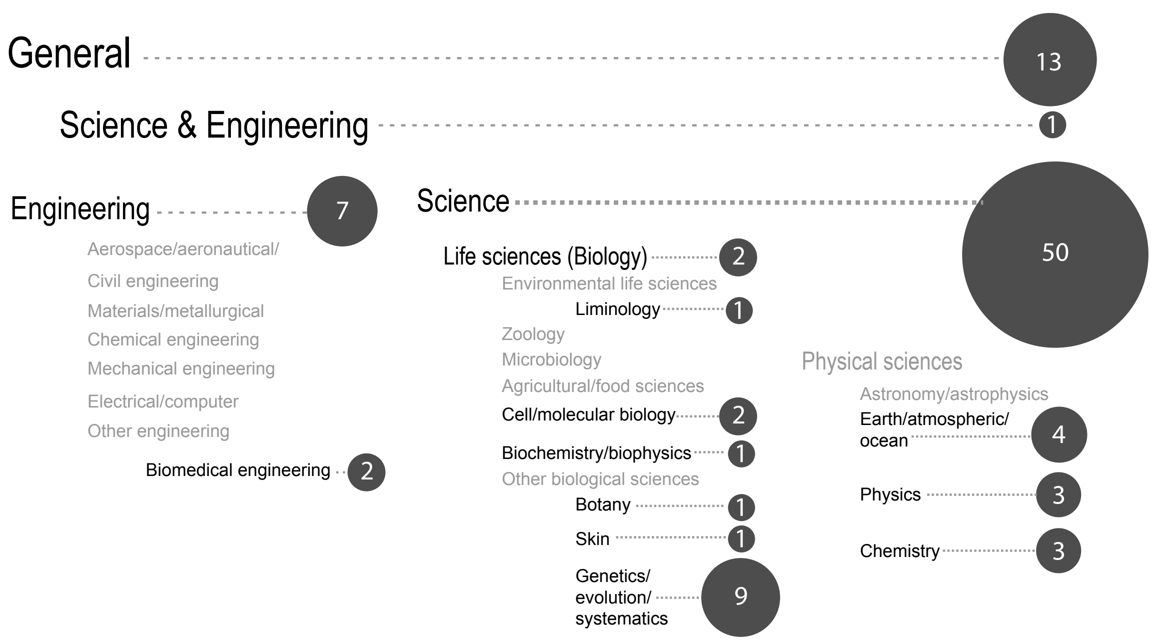


Figure 16: Disciplines referenced in the publications included in the integrative literature review. The circles indicate the number of contributions. "General" refers to publications

FINDINGS FROM THIS LITERATURE REVIEW (WITH CORROBORATION FROM THE EMPIRICAL STUDY)

Despite the diversity of perspectives and approaches represented in the literature, a set of coherent themes were identified. These themes fit into four broad categories:

1. Visuals enable comprehension (make it easier to absorb and understand new concepts)
2. Visuals enhance cognition (trigger new insights and thoughts)
3. Visuals facilitate communication (allow productive interactions between scientists)
4. Visuals improve memorability

Note that these categories fit a characterization of science as an endeavor of broadly distributed cognition in which knowledge is increased by enabling individuals to understand and build on the intellectual achievements of others through documenting and distributing those achievements in the form of verbal and visual representations. They are interdependent concepts—they happen simultaneously and they build upon and interact with each other.

Figure 17 shows the four categories and 10 themes. They are also listed in text form below, and then described in more depth along with comments from the interviews that corroborate them. The comments were made in response to a question about why the participant ranked visuals as being important in learning and teaching science.

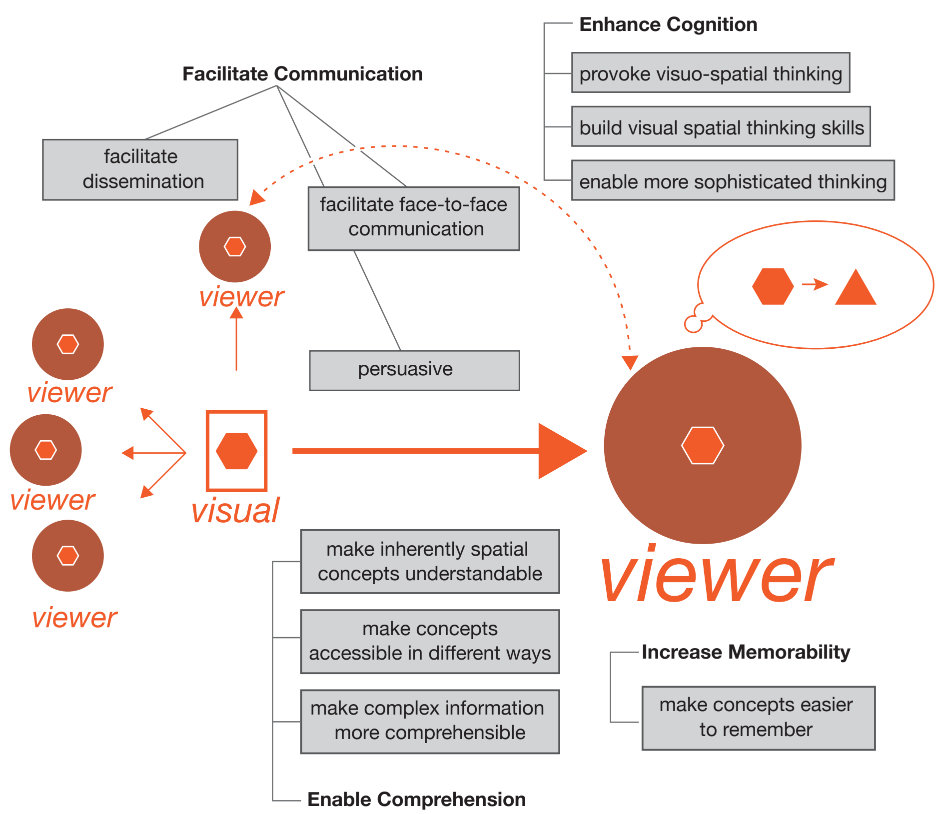


Figure 17: The four categories and 10 themes related to desired impacts of science visuals

CATEGORY 1. Enable Comprehension

Theme A1: A desired impact of many scientific visuals is to enhance understanding by providing access to concepts that are inherently spatial

Theme A2: A desired impact of scientific visuals is to enhance understanding by making scientific concepts accessible in different ways

Theme A3: A desired impact of science visuals is to enhance understanding by making complex information more comprehensible

CATEGORY 2. Enhance Cognition

Theme A4: A desired impact of science visuals is to provoke a type of thinking that differs from the thinking provoked by verbal or mathematical representations

Theme A5: A desired impact of science visuals is to enable more sophisticated thinking

Theme A6: A desired impact of creating and using science visuals is to build visual spatial thinking skills

CATEGORY 3. Facilitate Communication

Theme A7: A desired impact of science visuals is to persuade the viewer (i.e. visuals have a rhetorical function)

Theme A8: A desired impact of science visuals is to facilitate face-to-face communication

Theme A9: A desired impact of science visuals is to more successfully disseminate information

CATEGORY 4. Improve Memorability

Theme A10: A desired impact of science visuals is to make information more memorable

CATEGORY 1. Improve comprehension

Improving comprehension refers to facilitating the process of taking in and understanding scientific concepts, thereby increasing knowledge amongst scientists.

> Science is not just about truthfully describing or trying to replicate reality, but about making it more understandable and accessible in a [sic] myriad ways. —Luc Pauwels (2006b, p. viii).

Theme A1: A desired impact of many scientific visuals is to enhance understanding by providing access to concepts that are inherently spatial

This theme refers to the fact that some scientific concepts are inherently spatial (e.g. the structure of a protein molecule or the migration pattern of a species), and a visual representation is the only practical way to represent them; a verbal or mathematical representation is not a viable option. The following two examples from the literature restate this theme in the context of two scientific disciplines. The first is from a book by Nobel prize-winning chemist Roald Hoffman in which he talks about the importance of visual representations in chemistry: "The structural information that chemists need to communicate is at some important level inherently graphic—it is essentially a shape to be drawn" (Hoffmann, 1995, p. 69). The second is from a book by physicist and philosopher John Ziman, about the credibility of knowledge produced by science. In a chapter on maps he talks about the inherently spatial nature of geology knowledge: "a great part of 'what is known' to the science of geology is precisely what is to be found on a map…all the essential information about the topographical relations of the various mineral species is in the map itself…" (Ziman, 1978, pp. 78-79).

This theme expressed in the empirical study:

Eight of the 22 interview participants said that some science concepts are difficult to express in non-visual form. They did not characterize these as spatial concepts, but the examples they gave refer to spatial concepts. Here are 2 of these comments:

> …there are some diagrams in quantum mechanics, it's really hard to represent in terms of equations. But if you draw a diagram, the concept is very clear. And say for topology, which I don't know much, it's really hard if you don't see some [not] you know, circularly round some particular way, but I can't even imagine how could you explain it in print text. —Participant #5 (Astronomy), second interview

> In the work that I do, I think they're extremely important. Because it is a very like, you know, the water resources and civil engineering work that I do is very physical work like you, you're talking about, you know, precipitation or stream-flow or reservoirs or whatever. You have to be able to see what it is that you're talking about for it to make any sense. Um, so and there's all kinds of date-spatial scales that we're dealing with, so I think it's definitely an area that lends itself to graphics and visual thinking. —Participant #12 (Civil Engineering), first interview

Theme A2: A desired impact of scientific visuals is to enhance understanding by making scientific concepts accessible in different ways

This theme refers to the idea that visual representations of information have different impacts on the viewer than other forms of representation, even if the information represented is otherwise identical. For example a set of numbers can be presented as a table or as a scatterplot, but one provides access to precise values while the other reveals the structure or pattern in those values. I will give three examples of this theme in the literature. The first is from William Shea, a science historian who makes this point in the introduction to his edited book *Science and the visual image in the enlightenment*. The book explores the roles illustrations played in the creation and dissemination of scientific knowledge in the Eighteenth Century. "Scientific illustrations as images are indeed meant to be seen with associated texts, but they do not exist solely to shed light on printed matter. Both text and pictures convey information and are sources of knowledge. In some cases the pictures do most of the work; and scientific concepts are often best presented diagrammatically" (Shea, 2000, p. vii). The second is from philosophers James Griesemer and William Wimsatt who suggest that "visualization can provide handles for a mode of conceptualization which language lacks" (Griesemer & Wimsatt, 1989, p. 98). The third example is from Jay Lemke, who has a PhD in theoretical physics and studies communication and literacy in science. He also makes the point that different forms of representation are not interchangeable: "This is not the way scientific communication appears to work: meanings are made by the joint co-deployment of two or more semiotic modalities, and such co-deployment of resources is likewise needed for canonical interpretation. In my opinion, semiotic modalities (e.g. language, depiction) are essentially incommensurable: no verbal text can construct the same meaning as a picture, no mathematical graph carries the same meaning as an equation, no verbal description makes the same sense as an action performed" (Lemke, 1998, p. 110).

This theme expressed in the empirical study:

> So visuals are extremely important. Just because...yeah you can just look at it in a different way that numbers just don't give. —Participant #9 (Atomic Physics), second interview

Theme A3: A desired impact of science visuals is to enhance understanding by making complex information more comprehensible

Subtheme *3* is about making complex information accessible by simplifying it in visual form. I will give three examples of this theme in the literature. The first is from Bruno Latour, a philosopher who studies the evolution of scientific practice: "Scientists start seeing something once they stop looking at nature and look exclusively and obsessively at prints and flat inscriptions. In the debates around perception, what is always forgotten is this simple drift from watching confusing three-dimensional objects, to inspecting two dimensional images which have been made less confusing" (Bruno Latour, 1986, p. 15). The second is from Michael Lynch, a sociologist who studies scientists interacting with visual representations in their laboratories, "Visual displays are not only valuable as illustrations in scientific texts; they are irreplaceable as documents which enable objects of study to be initially perceived and analyzed" (Lynch, 1985, p. 37). He refers to turning specimens into 'docile objects' for purposes of investigation. The third is from Jane Mainschein, a biologist who analyzed differences between E.B. Wilson's early representations of cells, which were mostly photographs, and his later representations, which included more abstract and schematic drawings. He came to realize that "One can actually depict the essence of the idea better with a diagram in some cases. Photographs and drawings present the 'facts' themselves, while diagrams present abstracted and generalized interpreted information and theoretical ideas" (Maienschein, 1991, p. 253).

This theme expressed in the empirical study:

> They're so much easier to look at than an equation. You might look at an equation, but it's hard to just understand what that's going to do. So if someone just presents me an equation that's got, say like a decaying sinusoid. I look at this equation and I see like an e to the minus something, I see a sine, I'm trying to piece what it's going to look like, but I don't know the relative scales of like what's in the exponent and what's in the sine, so I don't know how fast it's oscillating and I don't know how quickly it's decaying. So those set the scale of what the graph will look like and that's really important. So you don't know if it decays before it even oscillates once, or if it's oscillated 50 million times before it's fallen to half of its normal value. So looking at a graph, like seeing an equation and looking at a graph—boom. You now understand how this system works. —Participant #9 (Atomic Physics), first interview

> Also, finally, science is often lots and lots of data. Not always, but it is often lots of data and people's brains are so good at picking up patterns, um that it would be a shame to just have people reading numbers when their brain is already this computer that make a plot and the brain can see everything you need it to see. —Participant #11 (Earth Sciences), first interview

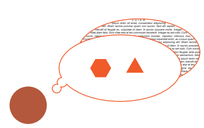
> ...if you're doing experiments that have to do with, you know, real life stuff you can see like, oh, this is what that looks like...and this is how they interact these are...they're comparable sizes, you can get a better idea of um, all the factors that go into it. —Participant #14 (Biophysics), second interview

CATEGORY 2. Enhance cognition

This category refers to the idea that a desired impact of science visuals is to help scientist think; to deepen or expand cognition in order to produce insight and understanding that go beyond what is represented.

> Scientists do not reason in the abstract. Their day-to-day work (partially) consists in producing representations—equations, diagrams, schematic drawings, etc.—of the phenomena they study. By manipulating these representations they draw inferences in order to predict and explain these phenomena —Marion Vorms (2012, p. 3 of manuscript).

The themes in this category are somewhat parallel to the themes in the previous category and they overlap to some degree, but they are separated because there is an important distinction: the themes in this category refer to the mental work scientists do to generate new ideas and understanding rather than the mental work scientists do to understand existing ideas.



Theme A4: A desired impact of science visuals is to provoke a type of thinking that differs from the thinking provoked by verbal or mathematical representations

The type of thinking evoked by visuals is referred to as *visual spatial thinking*, or *diagrammatic reasoning*.

Cognitive psychologist Roger Shepard, whose many contributions include seminal work on how we mentally manipulate 3-dimensional objects has studied the importance of visual thinking in scientific discovery: “many of the greatest scientists have emphasized that the processes that led to their inventions, discoveries, and theories were neither linguistic nor mathematical and, indeed, even when they knew that they had reached the crucial insight, they often had to struggle in order to cast their insight into the communicable form of words or mathematical symbols (…) I have argued that such a process makes use of perceptual mechanisms that have, through evolutionary eons, deeply internalized an intuitive wisdom about the way things transform in the world” (Shepard, 1988, p. 180). I will give two examples of this theme in the literature. The first is from Letitia Meynell, a philosopher who analyzed the role of Feynman diagrams—a form of notational representation of the behavior of subatomic particles shown in Figure 18:

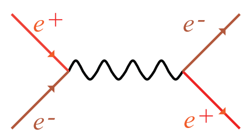


Figure 18: Example of a Feynman diagram

She argues that one of the functions of these diagrams is to facilitate thought: “What are characterized by Kaiser as ‘physical interpretations’ and ‘intuitive appeal’ can now be seen as the result of Feynman diagrams being effective props for generating imaginings of the quantum world” (Meynell, 2008, p. 51). A second example is from Kim Kastens and Toru Ishikawa who combine their expertise in geoscience and cognitive psychology to identify and categorize the various forms of visual-spatial thinking used by geoscientists. In addition to using visual spatial thinking to interpret representations of 3-dimensional, geophysical processes, they talk about using visual spatial thinking with representations of non-spatial phenomena. One of their examples is a data plot showing temperature versus salinity: “The mental processes for thinking about these non-distance-denominated ‘geospaces’ feel similar to the thought processes for thinking about distribution of, and movement through, regular distance-space” (Kastens & Ishikawa, 2006, p. 72).

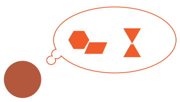
This theme expressed in the empirical study:

> I...it's just the way I learn, it's the way that makes the most sense. And that's the way I always approach problems from a young age. And the...that's what got me into physics. It was actually incredibly dorky. I was, um, I was with another friend and he was in physics...this was in high school. And he had a homework assignment and I said 'oh what's that' he said 'oh, well, what I'm trying to do is figure out the torque or the...it was probably the force...the strain on a rope as I'm swinging a rock around and I said 'oh, that's awesome, I want to know how to do that'. You know and it was a very visual start and that's.....yeah, I believe that's just the way I always thought about things, you know you...it's not you have the math

> and then you relate it to the world, you have the world and then you relate that to math. —Participant # 21 (nuclear physics) first interview

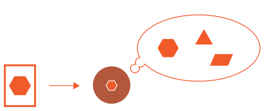
Theme A5: A desired impact of science visuals is to enable more sophisticated thinking

This theme refers to the idea that, apart from enabling a different *type* of thinking (theme A4), visuals can enable *deeper,* or *more sophisticated* thinking by freeing up cognitive resources. I will give three examples of this theme in the literature. The first is from philosophers James Griesemer and William Wimsatt, who make the case that visuals can function as heuristic tools – as cognitive short-cuts for problem solving, which make them "very 'cost-effective' in terms of demands on memory, computation, or other limited resources" by transforming a problem into a "non-equivalent, but intuitively related" problem which can be solved with less effort (Griesemer & Wimsatt, 1989, pp. 99-100). The second is from another philosopher, Ronald Giere, who argues that visuals free up cognitive resources for scientific thinking by acting as analogies or models that organize relevant information in memory. He uses an example from geology to make this point: "Wegener's presentation makes it clear both that the images played a large role in his own thinking and that he expected them to play a role in the thinking of his audience as well. But what is that role? The images, I suggest, function as partial visual models of the relevant features of the earth. As such they provide grounds for model-based judgments about the physical probabilities that would be operative in the world if it were structured according to the model" (Giere, 1996, p. 284). The third is from geoscientist Kim Kastens and cognitive psychologist Toru Ishikawa who refer to visuals as analogies that support thinking about complex phenomena either via simplified, idealized versions of a complex phenomenon or by relating an unobservable phenomena to an observable one (Kastens & Ishikawa, 2006).



This theme expressed in the empirical study:

This theme was not expressed in the empirical study.



Theme A6: A desired impact of creating and using science visuals is to build visual spatial thinking skills

This theme refers to the idea that one of the benefits of creating and using visuals is that it helps to build visual-spatial skills (the skills referred in theme A4). Since this theme emphasizes the value of learning to *create* visuals in addition to the impact of *viewing* visuals, it feels slightly out-of-place amongst the other themes. It is included because it appears repeatedly in the literature and it fits under the general heading *desired impacts of science visuals.* I will give three examples of this theme in the literature. The first is from *A History of Engineering Drawing* by engineer Jeffrey Booker. He argues that "we tend to think in terms of the languages we know. Drawing is of this nature, and he who can draw can think of, and deal with, many things and problems which another man cannot" (Booker, 1979, p. xv). The second example is from the preface to *Visual Representations, Visual Culture, and Computer Graphics in Design Engineering* by Kathryn Henderson, a sociologist who studies science and engineering. She writes "My years spent learning to sketch and draw made it clear to me that artistic rendering skills were not enrichment frills that were so trivial that school boards could cut them with impunity. I suspected, rather, that they were connected to cognitive skills as basic as mathematics and verbal literacy and equally applicable to all sorts of problem solving-in math and science as well as the visual arts" (Henderson, 1998, p. vii).

This theme expressed in the empirical study:

This theme is not explicitly addressed in the students' comments. None of the participants mentioned visuo-spatial skills. However, it is relevant to note here that six of the interview participants—all of whom had physics backgrounds—referred to the value of creating sketches that show spatial relationships as a basis for understanding or problem-solving.

> When I see a picture, I can imagine it a lot better instantaneously. But if I have to listen and try to make the picture in my head, that's a lot harder for me. So I always draw things out when I can. —Participant # 5 (Atomic physics), first interview

> Just drawing a picture is the first step of solving a problem and it's still the first step of solving a problem when doing research. —Participant #13 (Biophysics), first interview

CATEGORY 3. Facilitate communication

This theme refers to promoting the successful exchange of information between scientists as a desirable outcome of science visuals.

> Since science is more than personal knowledge, it can consist only of what can be communicated from person to person. —John Ziman (1978, p. 11)

Theme A7: A desired impact of science visuals is to persuade the viewer (i.e. visuals have a rhetorical function)

This theme refers to role visuals play in making the message compelling – enticing the viewer to absorb and accept that message. I will provide three examples of this theme in the literature. The first is from Bruno Latour, the philosopher quoted previously who refers to "the unique advantage they give in the rhetorical or polemical situation. 'You doubt of what I say? I will show you.' And, without moving more than a few inches, I unfold in front of your eyes figures, diagrams, plates, texts, silhouettes, and then and there present things that are far away and with which some sort of two-way connection has now been established" (Bruno Latour, 1986, p. 13). The second is from the introduction to *Visual Communication: More than Meets the Eye* by Harry Jamieson, professor of communication studies with a background in art education and expertise in visual perception. He suggests that visuals have this advantage because they are perceived directly:

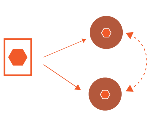
"…it is the attachment to the sensory world and its immediacy that gives visual communication its special niche" (Jamieson, 2007, p. 11). The third example is from sociologists and historians Alberto Cambrosio, Daniel Jacobi and Peter Keating. They analyzed Linus Pauling's use of visuals in the highly influential article that introduced his theory of antibody formation. The authors make the case that visuals can act as argumentative devices that persuade by engaging the viewer in the process of figuring out the logic of the argument themselves: "Our analysis of visual-argumentative structures shows, however, that in the case of visuals these two stages of argumentation [the constitution of a common frame of reference followed by attempts to impose one's point of view] are superimposed and intertwined: drawings and figures, in a kind of synergy designed to amplify their efficiency, simultaneously summon up and conflate these two stages" (Cambrosio et al., 2005, p. 190).

This theme expressed in the empirical study:

The following quotes from the empirical study refer to appealing to the audience by making the presentation more engaging (in the first quote) or more impressive (in the second):

> I guess um, yeah, if you take away the, you know, the visual media then, yeah, just text is so dry. I mean uh, I guess the....so I haven't had a lot of teaching experience um, but one of the...you know when you're presenting a conference paper you have at least in most conferences, you've got your 15-20 minute slot right and so, you're trying to teach people something. You're trying to get them excited about whatever it is that you did so they would go and read your paper or talk to you whatever. Um, and so in that, you know sort of short amount of time, you need something pretty engaging. So visuals are just, you know, way more engaging than anything else. —Participant #8 (Computer Science), second interview

> Um, I just think it's, it's the best way to really convey information and it really works better than any other method and if you are able to do that and do it effectively, you can really, um, you can really wow your audience in a good way. And really kind of bring them with you in what you've learned. Um, whereas if you don't do that effectively, you can actually upset your audience and get them frustrated and have them be totally not interested in what you have to say so, so yeah. —Participant #4 (Chemistry), second interview



Theme A8: A desired impact of science visuals is to facilitate face-to-face communication

This theme refers to the role of visuals in situations in which two or more individuals are interacting with a visual present. I will give three examples of this theme in the literature. The first is from anthropologists Marko Monteiro and Elizabeth Keating who studied a multidisciplinary team of scientists working together to build a biomedical device (Monteiro, 2010a, 2010b; Monteiro & Keating, 2009). They found that differences of interpretation would surface when the group interacted in the presence of a visual, and that this served the valuable function of enabling the group to address these differences in order to build shared understandings or to learn to communicate around differences: "The idea of productive misunderstandings as a way to interpret these processes, seeks to indicate how the mismatch and partial understandings that are a part of communication events in the meetings are more than miscommunication: They are rather productive sites for the identification of erroneous interpretations, illumination of unshared premises (which can then be mitigated) and development of shared understandings of what the common goals of the project are" (Monteiro & Keating, 2009, pp. 24-25). The second example is from sociologist Robert Kozma who describes an exchange between two chemists in which they move from initial disagreement to eventual common understanding while repeatedly referring to features in a set of visual representations to justify their interpretations. Kozma refers to the visuals as having both social and cognitive affordances that allow them to serve this supportive role: "…this segment [description of a portion of an interaction between two scientists using visuals] also illustrates the rhetorical—and consequently social—nature of this coordination process and the role that the material features of the representations play in affording it " (Kozma, 2003, p. 213). The third example is from sociologist Roger Krohn who, like Kozma, observed scientists using visuals to facilitate conversations in the laboratory, in this case a limnology laboratory. He describes what happens as "transformations among the media of experience and communication" in which the visual representations (in this case data graphs) trigger the viewer's knowledge of the phenomena behind the data (turbulent water, algae and micronutrients), which the viewer then transforms into the medium of language to share that knowledge (Krohn, 1991, p. 197).

This theme expressed in the empirical study:

The following two quotes refer to the use of a visual to facilitate an interaction:

> I tried to explain to people in different fields just in words before. It goes much better with the visuals. —Participant #2 (Botany), second interview

> What I'm reading and imagining might be very different from what you're reading and imagining, but if we both look at the same image, that's when we're sort of aligned with the same message. —Participant #10 (Civil engineering), first interview

Theme A9: A desired impact of science visuals is to more successfully disseminate information

This theme refers to the idea that a concept can be spread amongst scientists more successfully if it is captured in visual form. I give two examples of this theme in the literature—one that refers to the embodied qualities of visuals, and one that refers to the persuasive qualities of visuals. The first is from philosopher Bruno Latour who refers to visuals as "immutable mobiles" and lists amongst their valuable qualities the fact that "They can be reproduced and spread at little cost, so that all the instants of time and all the places in space can be gathered in another time and place" (Bruno Latour, 1986, p. 19) The second is from philosophers James Griesemer and William Wimsat who argue that an effective visual representation can make an idea or theory more successful in terms of being widely disseminated than an equally valid idea expressed only in verbal form partly because a visual can be easily reused in new contexts. It "has a greater chance of being able to migrate into and successfully colonize new contexts" than other forms of representation (Griesemer & Wimsatt, 1989, p. 97).

This theme expressed in the empirical study:

This theme did not appear in the empirical study. When asked about why they considered visuals important in science, none of the students addressed the value of visuals for disseminating ideas.

CATEGORY 4: Improve memorability

The preceding 9 themes were all present in the *Science Visuals* literature. An additional theme which is related to the desired impacts of science visuals but does not appear prominently in the *Science Visuals* literature is that *a desired impact of science visuals is to make information more memorable* (theme A10). This theme *is* reasonably prominent in the interview comments; 6 of the 22 interview participants said that visuals were valuable because they make science information easier to remember:

> There's something about images that...maybe this is just the way my brain works. I don't have photographic memory, I don't think of myself as a particularly visual learner. But I feel like there is a certain kind of resonance that images have. Like I can remember images from when I took biology in college 8-9 years ago now. And there's no reason for me to remember this diagram of a cell, but it takes up a whole page and its color and it's got all these complicated things in it. And, yeah, it just kind of sticks with you. —Participant #8 (Computer science), first interview

> I even remember back to my undergrad days is, I don't know, we were studying the cardiovascular system or something like, I don't know some cascade of biochemistry or whatever and rather than like 10 pages of notes detailing it, I would try and take those notes and put them into like a diagram. I mean, it would be pretty complex, it would probably be too much in a figure, but it's just the way....cause when I went to remember it, I mean obviously you have to understand something, but a lot of the details you have to recollect, kind of regurgitate, I can almost imagine a figure and a diagram kind of work your way through it. —Participant #3 (Rehabilitation Medicine), first interview

> And that's what helps me remember it or reason...or remember well enough that I could reason my way through to it the next time around versus remembering a billion different random facts. Often with a plot, if you can come up with the right one, you've managed to reduce your billion facts to one image that hangs together on its own. —Participant #22 (Earth sciences), first interview

This theme does not fit into the three existing categories, so it requires a fourth category: Improving Memorability.

SUMMARY

To summarize, the desired impacts of science visuals as expressed in the literature and empirical study fit into 4 categories:

1. Enable comprehension: A desired impact of science visuals is to improve comprehension by presenting information in a simplified form, a form that is qualitative different than verbal information, a form that provides direct access to inherently spatial information.
2. Enhance cognition: A desired impact of science visuals is to facilitate cognition by provoking visual-spatial thinking which can enable deeper or more sophisticated thinking and concurrently develop visual-spatial thinking skills.
3. Facilitate communication: A desired impact of science visuals is to facilitate communication by presenting information in a form that is persuasive, a form that facilitates dissemination and a form that enhances interpersonal interaction.
4. Improve memorability: A desired impact of science visuals is to make science concepts more memorable

CHAPTER 7: WHAT ARE THE CHARACTERISTICS OF *EFFECTIVE* VISUALS?

In this chapter, the second of four chapters presenting the findings related to each of the research questions, I present the findings related to the question "What are the characteristics of an effective visual – a visual that will have the desired impacts?" The bulk of this chapter is devoted to describing the 9 themes identified from the integrative literature review. At the end of the chapter is a description of how the findings from the empirical study align with these 9 themes, along with a description of a 10th theme that was not present in the integrative literature review.

INTEGRATIVE LITERATURE REVIEW

The search for literature that makes reference to the effectiveness of visuals produced a large and diverse group of documents. Applying the inclusion/exclusion criteria defined in chapter 4 reduced this to a subset of 125 to be included in the integrative literature review. These 125 documents are listed in Appendix 2.

Literature reviewed

The 144 authors of these 125 documents come from 15 disciplines as shown in Figure 19. Almost half (47%) are from psychology and an additional 18% are from education or educational psychology.

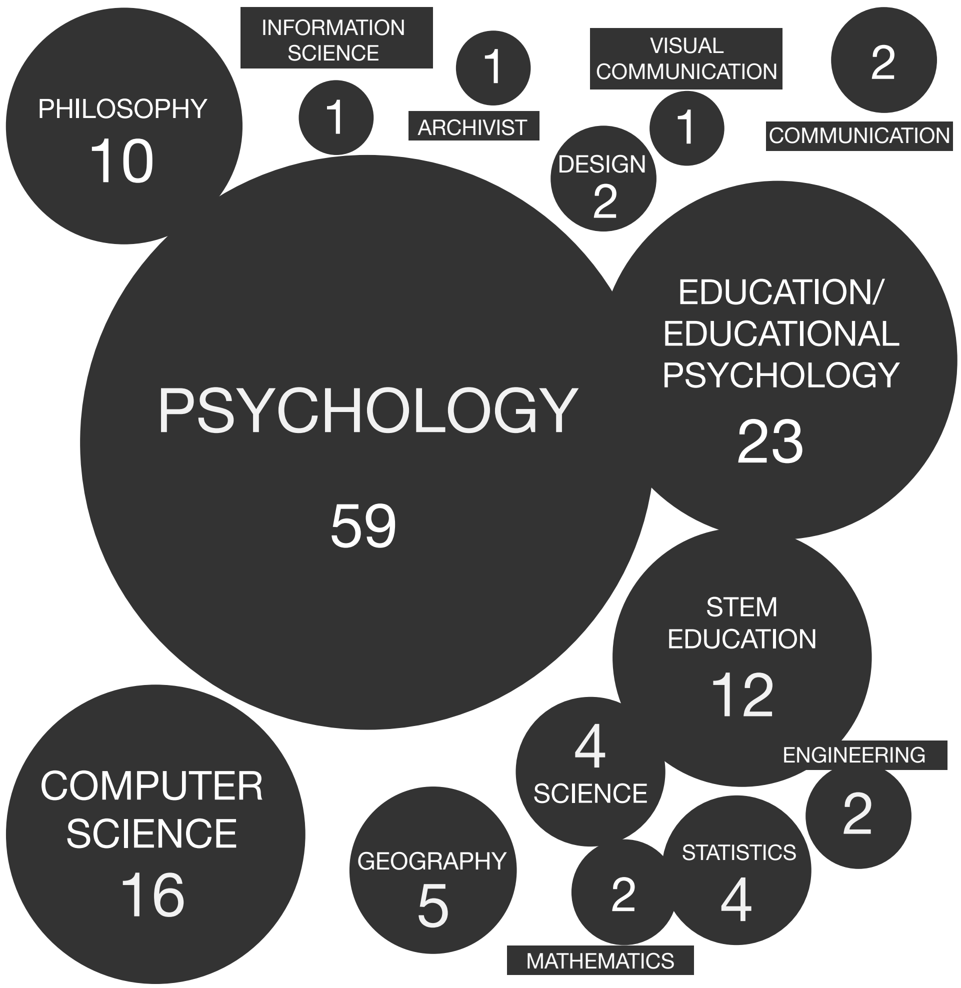


Figure 19: Author domains (size of bubble is proportional to the number of documents which is also indicated by the number)

Over half of these documents were published after 2003, as shown in figure 20, but there are also important contributions written much earlier including three that were published over 40 years ago: a chapter on *Graphic language* from a book on technical drawing (Giesecke, Mitchell, Spencer, & Merrell, 1958); a book entitled *Prints and visual communication* by William Ivins, retired curator of prints at the Metropolitan Museum of Art (1969); and a chapter on how we deduce function from appearance written by Richard Gregory, a pioneer in cognitive science (1970).

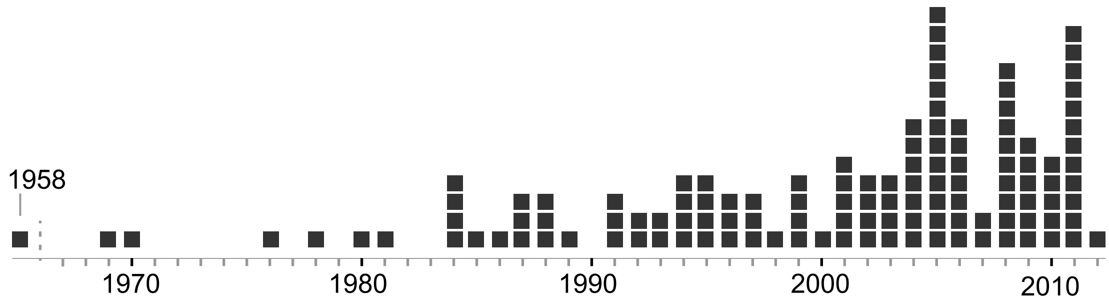


Figure 20: Publication dates of documents included in the Integrative Literature Review

The degree of diversity amongst these documents makes it difficult to characterize their content, but they can be clustered into 7 groups based on the types of questions they address:

What makes one visual more effective than another?

These are generally the results of laboratory experiments that compare different visuals to see if/how they evoke different responses: more accurate interpretation, faster comprehension, better transfer of knowledge to other tasks, better memory etc. An example of this is Cleveland & McGill's examination of our ability to quickly and accurately interpret data graphs based upon the types of perceptual skills they rely on (1984). Another is Lowe & Boucheix's article examining the effects of visual highlighting strategies on the viewer's attention (2011).

In what ways are visual representations different than or better than verbal representations?

These writings tend to talk about visuals in general rather than individual visuals (e.g. "visuals are more memorable than verbal representations" rather than "visuals with these characteristics are more memorable than verbal representations"). As a result, the findings are less directly applicable for making design decisions, although they *do* help identify contexts in which a visual might be useful. An example is Scheiter, Wiebe & Holsanova's chapter on *Theoretical and instructional aspects of learning with visualization*, which is an extensive summary of prior writings about how visuals differ from text (2008).

How do visuals work with language?

This is a small body of literature that looks at how accompanying text can contribute to making a visual effective. The dominant author in this area is Richard Mayer who has developed a series of guidelines for effectively integrating words and visual elements (2008).

How are visuals interpreted?

This literature helps us understand how viewers extract meaning from different forms of visual representation. An example is Elgin's article, which explores the complexity of the interpretation process as well as the complexity of representation (1984).

What makes visuals difficult to interpret?

This literature tends to focus on why science students misinterpret visuals – generally related their lack of familiarity with display conventions and limited conceptual understanding, but there are implications for the design of visuals intended for practicing scientists as well. An important example is Roth & Bowen's article that looks at errors made by established scientists as they interpret graphs outside of their field of expertise (2001).

How do visuals represent? What do visuals represent?

This literature addresses the inverse of the question "How are visuals interpreted?" It looks at how information is captured in visual form. An example is Alesandrini's article, which classifies visuals based on whether they are direct representations, analogies, or arbitrary representations (e.g. diagrams or graphs), and considers how different types of representation are appropriate for different types of tasks (1984).

How do visuals facilitate cognition?

One of the desired impacts of science visuals, as identified in chapter 6, is to facilitate cognition. This literature looks at mechanisms for doing so. It includes topics such as how visuals facilitate the creation of mental models, how they reduce the cognitive effort required for learning and how they facilitate analogical thinking. An example is Zhang's article, which presents a framework for how visuals, as external representations, interact with internal representations to facilitate problem solving (1997). Another example is Larkin & Simon's article, which identifies the qualities of visuals that enable them to be more computationally efficient than verbal representations (1987).

Finding coherence in the set of themes identified in this diverse body of literature is a challenging task partly because the contributions address such different questions and partly because this is not a clearly defined area of research. Even within a set of articles that address a similar question, each tends to stand alone, offering a unique approach or perspective. W. Howard Levie's quote is relevant here: "An aerial view of the picture research literature would look like a group of small topical islands with only a few connecting bridges in between" (1987, p. 26). Another reason this literature and the resulting themes are so disparate is that they reflect the nature of vision itself: although we experience vision as a unitary source of meaningful information, it actually consists of an array of functions that address tasks as dissimilar as detecting movement and retrieving memories (as summarized in chapter 3). It is therefore not surprising that it is difficult or impossible to identify a single organizing principle for the themes, and not surprising that coherence does emerge when these themes are organized around the architecture of visual cognition, which is how they are presented below.

FINDINGS FROM INTEGRATIVE LITERATURE REVIEW

Alignment with the architecture of vision and visual cognition

The description of vision and visual cognition presented in chapter 3 used the highly simplified diagram repeated below as Figure 21, which shows three major components: visual perception, working memory and long-term memory.

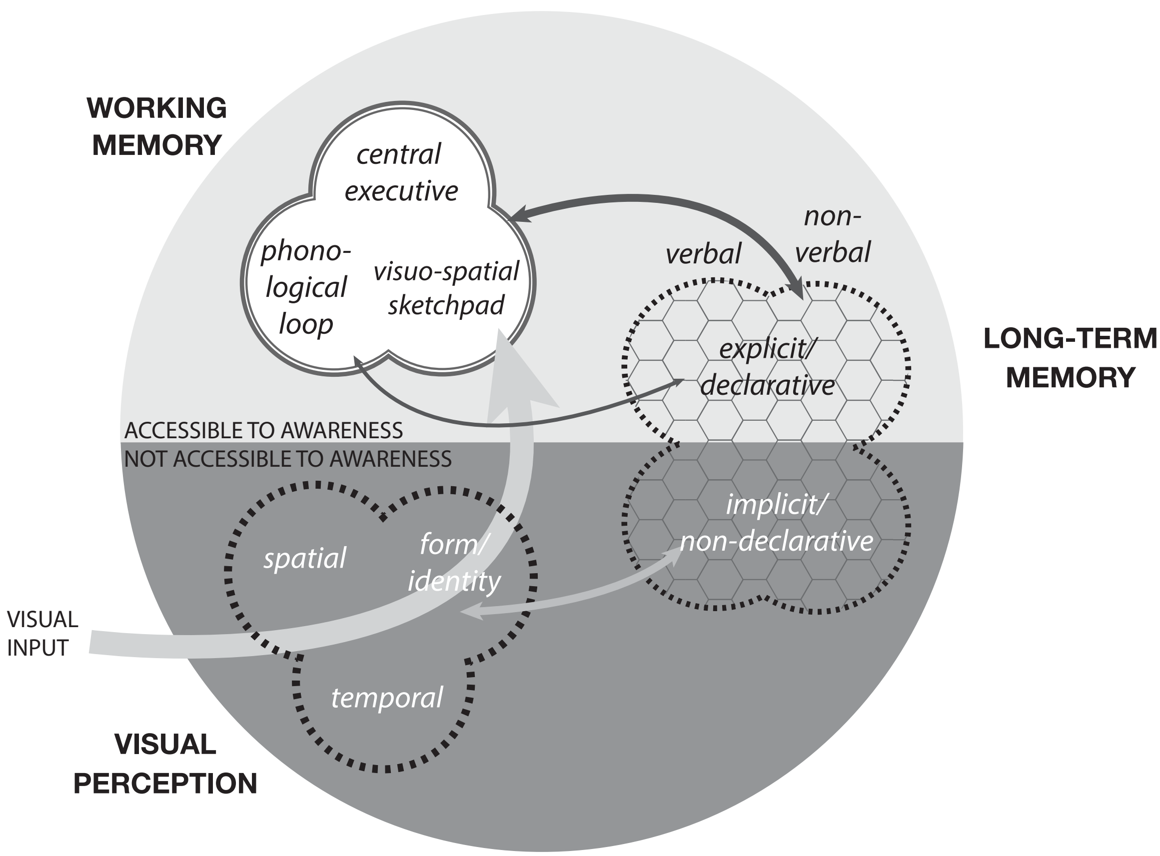


Figure 21: Major components of vision & visual cognition.

As I describe in detail below, when the 9 themes from the integrative literature review are aligned with the three components of vision and visual cognition, three principles emerge: an effective visual *maximizes* reliance on visual perception, *optimizes* retrieval from long-term memory, and *minimizes* demands on working memory. These principles are illustrated diagrammatically in Figure 22:

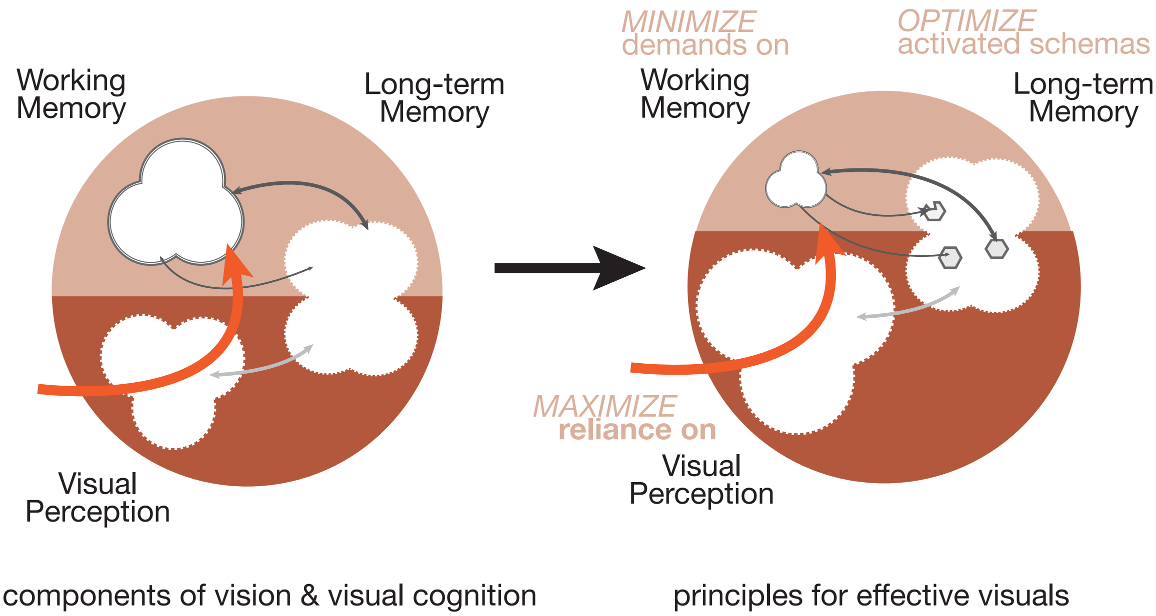


Figure 22 The diagram on the left shows the components of vision and visual cognition, and the diagram on the right shows the principles for effective visuals as they relate to these components: An effective visual maximizes reliance on visual perception, and optimizes activated schemas to minimize demands on working memory

The three principles derived from the integrative literature review and their associated themes are as follows:

PRINCIPLE 1. Maximize reliance on visual perception

Theme B1: An effective visual facilitates direct apprehension

Theme B2: An effective visual facilitates accurate characterization

Theme B3: An effective visual guides attention helpfully

PRINCIPLE 2: Minimize demands on working memory

Theme B4: An effective visual constrains thinking helpfully

Theme B5: An effective visual minimizes the amount of information that must be stored in short-term memory

Theme B6: An effective visual minimizes demands on working memory by excluding redundant information

PRINCIPLE 3. Optimize activated schemas (& build new/better schemas)

Theme B7: An effective visual evokes relevant knowledge/schemas

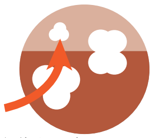
Theme B8: An effective visual is aligned with the viewer's knowledge & skills

Theme B9: An effective visual maximizes retention & recall

I describe each theme in detail below. For each, the literature generally includes a description of the concept and an explanation of how a visual facilitates the process or mechanism.

CATEGORY 1. Maximize reliance on visual perception

A characteristic of effective visuals is that they maximize reliance on visual perception



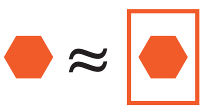
Theme B1: Facilitates direct apprehension through perceptual properties

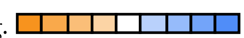
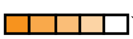
This theme refers to the idea that when information is conveyed via perceptual properties such as spatial relationships, color or size, it can be brought into awareness without placing demands on working memory. I will give three examples of this theme in the literature. The first is from Jiajie Zhang and Donald Norman, two cognitive psychologists who conducted a series of experiments in which the participants solved a puzzle using different representations of the puzzle pieces (1994). Some of these representations made the rules of the puzzle perceptually explicit (e.g., you could not put piece A on piece B because it would fall) while others relied on written rules that had to be memorized (e.g., you could not put piece A on piece B because the rule said that piece A could only be placed on piece C). Their conclusion was that "External representations can provide information that can be directly perceived and used without being interpreted and formulated explicitly" (p. 118). In other words, if you can represent the relevant parameters of a problem perceptually (e.g. one object can fit inside of another object), a visual representation will convey that information without requiring you to formulate mental propositions such as "x is larger than y in every dimension and therefore y will fit inside of x."

The second example is from Keith Stenning and Oliver Lemon, communication scientists, who refer to the "directness of semantic interpretation" that is possible when "the spatial relations between their tokens share structural properties with the (not necessarily spatial) relations between denoted objects in the target structure" (2001, p. 35). To explain what they mean by "directness," they give the example of a sentence in which the order of words in a phrase is significant, but based upon the context created by the other words in the phrase and rules of grammar, whereas the order of elements in a visual representation such as a timeline can reflect the order of those elements in the physical world with no intervening rule.

The third example is from Jill Larkin and Herbert Simon who analyze various types of diagrams and argue that "The fundamental difference between our diagrammatic and sentential representations is that the diagrammatic representation preserves explicitly the information about the topological and geometric relations among the components of the problem, while the sentential representation does not" (1987, p. 66). And as a result, "diagrams automatically support a large number of perceptual inferences, which are extremely easy for humans" (p. 99).

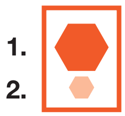
The literature also addresses the implications of this theme for creating effective visuals. I will provide two examples of this. The first, referenced earlier, is from William S. Cleveland and Robert McGill, both statisticians, who demonstrated that the ease and accuracy of our perceptions vary depending upon the nature of the perceptual task (1984). For example we do better at comparing values in a bar chart, which requires a judgment of relative height than comparing values in a pie chart, which requires a judgment of relative angle or wedge area. Their design recommendation is to choose a representation that relies the perceptual tasks we perform most quickly and accurately. The second example is from Barbara Tversky, Julie Morrison and Mireille Betrancourt, cognitive psychologists, who argue that animated visuals can fail to communicate effectively if they ask us to perceive information that is difficult for humans to detect in motion (2002). In another article, Tversky elaborates: "People do not know how to parse or perceive the animations that life naturally provides. The art museums of the world are filled with paintings of horses galloping with their legs incorrect [*sic*] configured" (2005b, p. 38). The design implication is that representations should rely on perceptual features that are "accurately perceived and appropriately conceived."


Theme B2: Facilitates accurate characterization through perceptual properties

The previous theme emphasizes the directness of perceptual apprehension. This theme refers to the idea that those directly perceived properties can convey relevant conceptual properties of the referent. This point is made in many of the writings referenced for the previously theme, but I will give two additional example here. The first is from an article by Cynthia Brewer, a geographer, who argues that the type of color scheme chosen to represent values displayed on a map should have perceptual qualities that are aligned with the conceptual qualities of the data set (1994a). For example, a divergent color scheme—one in which colors diverge from a central point (e.g.  *) should be used for a data set in which values diverge from a central point (e.g. rate of growth/decline in a population). A sequential color scheme – one in which colors have a natural sequence (e.g. ) should be used for a data set which has a natural sequence of values (e.g. almost any quantitative attribute that that starts at zero such as the concentration of particulates in the air or amount of rainfall). A binary color scheme (e.g ) should be used when there are just two data values (yes/no or true/false). A qualitative color scheme in which each color is distinct and

* For those viewing this without color, the first color scheme goes from saturated orange to saturated blue with white in the middle; the second color scheme goes from saturated orange to white, the third color scheme consists of blue and orange and the fourth color scheme consists of four distinct colors.

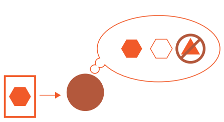
dissimilar (e.g. ) should be used when the data categories have no natural order (such as the vegetation types in a landscape). The second example is from Peter Cheng, an informatics specialist, who compared performance on a problem-solving task using either a diagrammatic representation, a verbal description or a tabular representation of pulleys and weights (2004). He concludes that "the representation should attempt to make the underlying structure of the problem readily apparent to the user. (…) an effective representation should attempt to encode the underlying relations, or meaning, of a domain directly in the structure of its representational schemes" (p. 259).



Theme B3: Guides attention helpfully

This theme refers to the idea that in a visual, elements can be made more or less prominent to convey their relative importance and thus influence the sequence of attention. This theme is only weakly supported in the literature analyzed, but it is well-established in the visual design world (a search on "visual hierarchy" will confirm this). I found two examples of this theme in the body of literature reviewed – one that showed positive evidence, and one that was inconclusive. The first is from Sara Fabrikant, a geographer, Stacy Hespanha, a geographer-psychologist, and Mary Hegarty, a psychologist (2010). They found experimental evidence that visual salience played a role in directing the attention of novice viewers interpreting a weather map (though it had no impact on expert viewers). The second example is from Richard Lowe and Jean-Michel Boucheix who found inconclusive results from an experiment in which they used color to attract a viewer's attention to important elements in an animated diagram (2011).

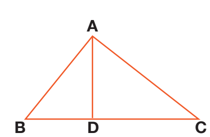
CATEGORY 2: Minimize demands on working memory



A characteristic of effective visuals is that they can be processed with minimal demands on working memory.

Theme B4: An effective visual constrains thinking helpfully

This theme refers to the idea that well-designed visuals constrain thinking or problem-solving in meaningful ways – preventing the waste of mental effort spent pursuing ideas that are less obviously wrong when presented in other ways. I will provide four examples of this theme in the literature. The first is from Robert Lindsay, a psychologist who specializes in artificial intelligence (1988). He argues that the functional role of imagery, in contrast to other forms of representation, is that the properties of the representation enable it to support inferences in a non-procedural, non-logic-based way that can be highly efficient. He gives the example of the geometric diagram shown here that makes it trivially easy to infer that the area of triangle ABD + the area of triangle ACD is equal to the area of triangle ABC. Part of this efficiency is a result



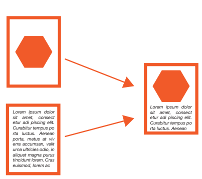
of the fact that a visual representation must include information that eliminates inferences that are more difficult to disprove with a verbal description and a procedural proof. As he puts it: "visual images possess properties (…) not possessed by deductive propositional representation, and these properties help avoid the combinatorial explosion of correct but trivial inferences that must be explicitly represented in a propositional system" (p. 231).

The second example is from the article quoted previously by cognitive scientists Keith Stenning & Oliver Lemon, who argue that "inexpressiveness in representation systems generally leads to tractability of inference" (2001, p. 30) They provide the following explanation: "As an illustrative example, most diagrammatic systems enforce the representation of all identity relations between represented objects, whereas sentential languages are, in general, expressive enough to abstract over identity relations. For example, the evening star may or may not be the morning star, but drawing a diagram which remains agnostic on the issue is difficult. Enforcement of identity relations enormously simplifies inference, as anyone will intuitively discover when holding a conversation using two names for which identity is actively unknown" (p. 30).

The third example is another from cognitive psychologists Jiajie Zhang and Donald Norman whose research demonstrates that visual representations can guide thinking: "The physical structures in external representations constrain the range of possible cognitive behaviors in the sense that some behaviors are allowed and others prohibited" (1994, p. 119).

The fourth example is from Nancy Nersessian, a cognitive scientist who studies how scientists think. She argues that elements present to the visual system offer affordances for making problem-solving easier (Nersessian, 2008). To make this point, she uses the everyday example of trying to decide if a sofa will fit through a doorway. She points out that the task is easiest in the presence of the doorway and the sofa since they can be re-inspected as needed.

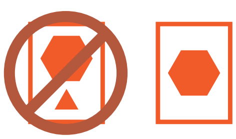
Theme B5: An effective visual minimizes the amount of information that must be stored in short-term memory



This theme refers to minimizing the amount of information that needs to be held in conscious awareness to facilitate cognitive work. The literature talks about two ways in which well-designed visuals can facilitate this.

One way is to avoid separating a visual from the text that accompanies it. I will give three examples of this theme in the literature. The first is from educational psychologists Rohani Tarmizi and John Sweller who conducted research on the performance effects of integrating text and geometry diagrams and introduced the idea of the *Split-Attention Effect*, which states that if pieces of information that need to be integrated for understanding are separated physically, performance will be degraded because of the mental effort required to maintain one piece of information in memory while navigating to the other (1988). The second example is also from John Sweller and a different colleague, Paul Chandler, who conducted additional research on the Split-Attention Effect with similar results using different types of diagrams (1991). The third is from Richard Mayer, an educational psychologist quoted previously, whose research has focused on integrating images and words for instruction. He refers to the value of integration across both space (which he refers to as the *Spatial Contiguity Effect*), and time (which he refers to as the *Temporal Contiguity Effect)*, and is achieved by presenting words aurally so they can be processed while simultaneously viewing a visual (2003).

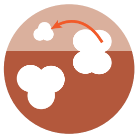
The second way visuals reduce the amount of information that must be held in conscious awareness is by virtue of their ability to function as external memory aids. J. Kevin O'Regan, a psychologist who studies vision argues that the visible world can be "considered as a kind of external memory store which can be accessed instantaneously by casting one's eyes (or one's attention) to some location" (1992, p. 461). An example of this in the literature reviewed is from Jiajie Zhang and Donald Norman. Their list of properties of external representations includes: "External representations can provide memory aids. For example, in all of the TOH [Tower of Hanoi—a reference to the puzzle they used] experiments reported here, the goal problem states did not need to be memorized, because they were placed in front of the subjects either by diagrams or by physical objects" (1994, p. 118).



Theme B6: An effective visual minimizes demands on working memory by excluding redundant information

This theme refers to the idea that when a visual includes information the viewer already possesses, it creates an unnecessary demand on working memory since the viewer must attend to that information in order to identify it as redundant. It is somewhat inaccurate to refer to this concept as a "theme" in this literature since it comes from the work of just one researcher and his colleagues, but I include it since it is of particular relevance to situations in which the viewer is an expert—as is often the case with science visuals. The research is by educational psychologists Slava Kalyuga, Paul Ayres, Paul Chandler, and John Sweller. They refer to this concept as the *Expertise Reversal Effect*. It emerged from experimental evidence showing that experts performed more poorly when additional information was added to displays, while novices performed better (Kalyuga, Ayres, Chandler, & Sweller, 2003). They theorize that the additional information creates a demand on working memory, but does not contribute to understanding since it is redundant with the expert's prior knowledge.

CATEGORY 3. Optimize activated schemas (& build new/better schemas)



Theme B7: An effective visual evokes relevant knowledge/schemas

> Enough has now been said to prove the general law of perception, which is this: that whilst part of what we perceive comes through our senses from the object before us, another part (and it may be the larger part) always comes out of our own mind. —William James (1892, p. 329)

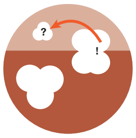
This theme refers to the idea that visual representations evoke or activate prior knowledge (structured as schemas), which is then used for interpretation. I will give four examples of this theme in the literature.

The first is from Daniel Schwartz, an educational psychologist who presented viewers with a problem-solving task using one of two illustrations of a hinge: either highly simplified line drawing (two lines connected at a point), or a more detailed, realistic drawing. He found evidence that the line drawing activated geometry schemas (relative line lengths and angles), whereas the realistic drawing activated schemas about hinges as familiar objects (1995).

The second example is from Jeff Zacks & Barbara Tversky, cognitive psychologists who presented participants with a data analysis task and one of two representations: either a bar graph or a line graph. They analyzed the written descriptions and found that the bar graph was more likely to trigger ideas about discrete data points while the line graph was more likely to trigger ideas about continuous trends (1999).

The third example is from M. Beveridge and E. Parkins, educational psychologists who sought to show that visuals could help viewers find solutions to problems by evoking knowledge of analogous problem-solutions. They presented different representations of multiple fire hoses dousing a single fire as an analogy to the use of multiple laser beams to destroy diseased tissue. They found that some representations were more effective than others at evoking a conceptualization that helped the viewer solve the problem; just showing converging fire hoses was not enough, the visual had to explicitly convey the point that where the fire-hoses converged, the intensity of the water was greater than elsewhere (Beveridge & Parkins, 1987).

The final example makes the point that it is also important to avoid evoking schemas that impede understanding. It comes from an article by psychologists Camillia Matuk and Daivd Uttal, who looked at experimental evidence for how students interpret or misinterpret evolutionary tree diagrams (cladograms). They argue that these representations are likely to cue inaccurate common-sense theories in novices: “Although cladograms can be powerful reasoning tools, they are not without their challenges. Experts familiar with both its content and its system of representation find them useful tools for reasoning about phylogenetic relationships; but for novices, they are more likely to cue intuitive folk theories of evolution. If introduced too early, the standard cladogram may thus hinder rather than help students develop proper phylogenetic reasoning skills " (2012, p. 137).



Theme B8: An effective visual is aligned with the viewer's knowledge & skills

This theme refers to the idea that an effective visual provides the viewer with the information they need while leveraging the knowledge they already possess. I will provide four examples of this theme in the literature. Each example refers to leveraging a different type of knowledge.

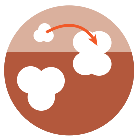
The first example is from educational psychologist Punyashloke Mishra in a chapter titled *The Role of Abstraction in Scientific Illustration: Implications for Pedagogy.* One type of knowledge he identifies as being useful for understanding science visuals is knowledge of cultural conventions: "…scientific illustrations function within the matrix of science, with its hidden assumptions and biases. Quite often these biases are invisible to us at this moment in time and thus are quite insidious in their effect" (1999, p. 193).

The second example refers to the importance of knowing which visual conventions the audience is or is not familiar with. It is from science historian Martin Rudwick in his article about the historical evolution of the visual language of geology. He emphasizes the importance of visual conventions for facilitating communication between specialists, but also notes that "geologists tend to treat their everyday use of geological maps as essentially natural and unproblematical, perhaps forgetting their own initial difficulties in learning to read such maps and the difficulties of teaching students to do the same" (1976, p. 151).

The third example refers to the importance of the viewer's experience with the subject matter. It is from cognitive psychologists Wolff-Michael Roth and G. Michael Bowen who found evidence that experienced scientists make the same types of interpretive errors as novices when viewing *familiar* graph types that present *unfamiliar* data (i.e. data from an area outside of their expertise). He argues that to fully understand the presentation the viewer must understand both the data itself and the context in which it was gathered (2001).

The fourth and final example refers to the importance of interpretation skills developed through exposure and experience. It is from Willi Dörfler, who studies mathematics education. The reference is to math diagrams, but could apply to many science visuals as well. His point is that some visuals are difficult to understand without skill developed from experience: "efficient and successful diagrammatic reasoning presupposes intensive and extensive experience with manipulating diagrams" (2004).

To summarize, these four examples present four forms of knowledge that need to be aligned with the viewer's knowledge: knowledge of cultural assumptions, knowledge of visual conventions, knowledge of content and the skill that comes from experience working with similar visuals.



Theme B9: An effective visual maximizes retention & recall

This theme challenges the premise that minimizing demands on working memory is always preferred. It is based on the idea that a desirable outcome of an encounter with a science visuals is retention of the message being conveyed, and that in order to create a memory, (i.e. in order to create new or enhanced schemas) one must actively engage with the information which means processing it in working memory. I'll provide two examples of this theme. The first is from an article by Jessica Hullman, an information scientist, Eytan Adar a computer scientist, and Priti Shah a psychologist (2011). They cite a number of studies that suggest that a visual that increases cognitive load in certain ways, such as introducing uncertainty and interpretation challenges, can increase engagement, learning and insight (2011). The second is a more implicit example of this theme. It is from an article by computer scientists Scott Bateman, Regan Mandryk, Carl Gutwin, Aaron Genest, David McDine, and Christopher Brooks. They conducted a series of experiments to test the notion espoused by some visualization experts that potentially distracting decorative embellishments should always be avoided. They found that long-term memory was greater for the decorated visuals (2010).

SUMMARY OF RESULTS FROM THE INTEGRATIVE LITERATURE REVIEW

To summarize, an effective visual influences processing in three ways: it maximizes reliance on visual perception by facilitating direct apprehension, by conveying conceptual qualities via perceptual qualities and by guiding attention with perceptual properties; it minimizes demands on working memory by constraining the range of viable solutions, by minimizing the need to hold information in memory temporarily and by excluding redundant information; and it optimizes the schemas that are evoked to facilitate interpretation and promote engagement for building new schemas.

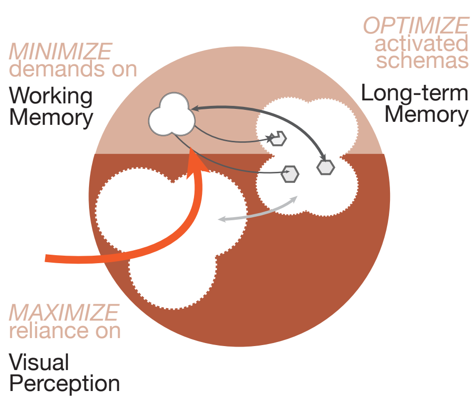


Figure 23: Principles of effective visuals from the integrative literature review

FINDINGS FROM THE EMPIRICAL STUDY

In the interviews, participants were asked "In your opinion, what makes a science visual successful or unsuccessful?" Figure 24 presents the 36 themes identified in the responses to this question clustered according to their general alignment with the categories identified in the literature. This alignment is as precise as possible, although not always solid given the lack of explanation that came with many of the comments. I'll first summarize the overall degree of alignment between the literature themes and the interview themes, then go in to more detail. There was good alignment with all three subthemes in category 1: *Maximize reliance on visual perception*. There was good alignment with two of the three themes in category 2: *Minimize demands on working memory*, but a lack of alignment with theme B4: *An effective visual guides attention helpfully*. There was relatively little alignment with the three themes in category 3: *Optimize activated schemas*, though some alignment with B8: *An effective visual is aligned with the viewer's knowledge and skill*. 12 themes were not clearly aligned with the themes from the literature. I will discuss this more below.

Alignment with CATEGORY 1: Maximize reliance on visual perception

As figure 24 shows, there were comments that aligned well with all three themes in this category. For example, 6 participants referred to the importance of having elements that are easy to discriminate (e.g. large enough or legible, which is one aspect of facilitating direct perception); 4 participants said that an effective visual reveals relationships (which is aligned with theme of accurately characterizing the information); and 6 participants said that an effective visual emphasizes important elements (consistent with the idea of guiding attention).

Alignment with CATEGORY 2: Minimize demands on working memory

12 of the 36 themes were related to minimizing demands on working memory. These included two of the three most frequently expressed themes: 9 participants said that an effective visual does not contain too much information and 8 participants said that an effective visual is simple and uncluttered. Both of these themes are aligned with theme B5: *An effective visual minimizes the amount of information that must be stored in short-term memory*. Another relatively prominent theme (expressed by 5 participants)—that in an effective visual, all extra information is excluded—is well aligned with theme B6: *An effective visual minimizes demands on working memory by excluding redundant information*. The remaining 5 themes were expressed by only one participant and were less well aligned with the themes identified in the literature. None of the themes were aligned with B4: *An effective visual constrains thinking helpfully*.

Theme	Subthemes
Maximize reliance on visual perception	
B1: An effective visual facilitates direct apprehension	conveys the message quickly easy to discriminate (e.g. legible) sensitive to color blindness works in B&W as well as color perceptually effective use of color
B2: An effective visual facilitates accurate characterization	reveals relationships doesn't distort or skew uses the appropriate type of graph
B3: An effective visual guides attention helpfully	emphasizes important elements has good visual hierarchy
Minimize demands on working memory	
B4: An effective visual constrains thinking helpfully	none
B5: An effective visual minimizes the amount of information that must be stored in short-term memory	doesn't contain too much information is simple & uncluttered is well-labeled is close to the corresponding text groups content when possible
B6: An effective visual minimizes demands on working memory by excluding redundant information	all extra information is excluded
Other	doesn't contain too little information is information dense is aligned with the message in the text has a clear central point unambiguous
Optimize activated schemas (& build new/better schemas)	
B7: An effective visual evokes relevant knowledge/schemas	none
B8: An effective visual is aligned with the viewer's knowledge & skills	builds on existing knowledge takes advantage of prior associations uses familiar conventions
B9: An effective visual maximizes retention & recall	none
Cue positive aesthetic/affective response	
B10: An effective visual has an appropriate aesthetic appeal	is visually appealing has an appropriate tone good composition/structure good use of negative space consistent with other visuals
Additional subthemes that are not clearly aligned with the literature	
	successfully conveys its message summarizes serves a function within presentation allow readers to draw own conclusions shows uncertainty (error bars) follow journal rules is inexpensive to reproduce

Figure 24: Themes in interview responses to the question: In your opinion, what makes a science visual successful or unsuccessful?

Alignment with CATEGORY 3: Optimize activated schemas (& build new/better schemas)

None of the responses from the interviews explicitly referred to drawing upon or building schemas, although 3 comments referred to effective visuals as complementing the viewer's pre-existing knowledge, which fits under theme B8: *An effective visual is aligned with the viewer's knowledge and skills*. It is also relevant to note that, while none of the participants described an effective visual as one which maximizes retention and recall (theme B9), 6 participants had previously said that one of the values of visuals was that they were more memorable than verbal representations.

Additional theme and category

I have added a 10th theme: *B10: An effective visual has an appropriate aesthetic appeal*, and a fourth category: *Cue positive aesthetic/affective response* to accommodate the substantial number of comments from the interviews (19) that were related to the aesthetic qualities of a visual. This is an area in which it is not always clear what the interviewee had in mind—6 of the comments may have been about perceptual effectiveness rather than aesthetic qualities, but 13 were unambiguously about aesthetic qualities: 7 participants said an effective visual is visually appealing and 6 said that an effective visual has an appropriate tone.

The importance of aesthetic appeal is prominent in professional design practice and, as described in chapter 3, there is evidence of a neurological mechanism by which affective responses influence perception and attention, but it did not emerge as a prominent theme in the *Effective Visuals* literature. It is not wholly absent, there is brief mention by Luc Pauwels, a communication scientist: "a visual representation may perform the function of an eye catcher, a means to arouse and maintain attention and interest, or even to entertain the reader/spectator (and thus bring them into the right mood for acceptance)" (2006a, p. 19).

Additional themes

The remaining 7 themes did not fit into any of these 4 categories. The most prominent one (expressed by half of the participants) was that an effective visual is one that successfully conveys its message. This is more about defining "effective" than about identifying qualities of an effective visual. Two themes referred to the role the visual plays within the context of the paper or presentation: 5 participants said a visual that summarizes the contents of a paper is an effective visual; and 2 participants said simply that a visual should serve a function within the paper/presentation. This brings in a larger perspective of the overall message in which the visual is embedded that has not been well-addressed in this dissertation and is worthy of more focused consideration in future work. The final two themes addressed pragmatic concerns: 3 participants said that an effective visual works well in black and white as well as color – a nod to the pragmatic reality that many people print out articles in black and white ink; and 3 participants said that an effective visual contains enough information—referring to experiences with visuals that did not have enough information to justify the space they occupied on the page.

Comments on the degree of alignment between the literature and interviews

As described above, there is some degree of alignment as well as some degree of divergence between the themes from the interviews and the themes from the literature. This lack of alignment is not necessarily problematic. The themes the students did not mention (e.g. B7: *An effective visual evokes relevant knowledge/schemas*) are ideas that came from focused research and are not necessarily intuitive. One of the questions that will be interesting to explore in future research will be whether conscious awareness of these themes contributes to competence in visual communication. The fact that the interview participants identified themes that were not present in the literature may reflect the bias in the literature toward a cognitive science perspective. As mentioned above, this is also an area worthy of further exploration.

CHAPTER 8: WHAT IS "COMPETENCE IN VISUAL COMMUNICATION?"

In this chapter, the third of the four chapters presenting the findings related to each of the research questions, I present the findings related to the question "What are the skills and knowledge that constitute competence in visual communication?" In contrast to the previous two chapters for which there was an extensive array of literature to draw from, the published literature related to this chapter is relatively sparse. It is split into two distinct groups—a subset of the literature from the previous, *Effective Visuals* literature, and small body of literature from researchers who study designers (22 documents listed in appendix 3). From these two bodies of literature, I identified 11 themes that correspond to 11 forms of skill/knowledge. In addition, I identified two themes from the empirical study. Figure 25 displays all 13 themes. They are overlaid on a diagram showing the elements involved in the creation-manifestation-interpretation of visuals, and they are colored to indicate whether they came from the *Effective Visuals* literature, the *Design and Design Education* literature or the empirical study.

There were a number of challenges involved in producing this list. The first arose from the fact that the state of our knowledge in this area is somewhat tenuous—there is little explicit or sustained discussion on this topic in the literature. This may reflect Donald Schon's observation that design educators "may find it extraordinarily difficult to give explicit, accurate, and useful accounts of the understandings implicit in gradually learned competences that have become intuitive" (Schon, 1985, p. 7). Because of this lack of explicit discussion I had to rely heavily upon my own experience of learning to create visuals to meaningfully interpret the evidence. I also relied on extensive conversations with others to minimize personal bias in these interpretations. Other challenges arose from the multi-faceted nature of visual communication. Just as it was difficult to identify a basis for organizing themes related to what makes visuals effective, it was difficult to identify a basis for organizing the knowledge and skills need for creating effective visuals.

One promising strategy is to base this organization upon the underlying categories of knowledge or skill they represent. These categories would include, for example *declarative knowledge* (knowing about) as well as *procedural knowledge* (knowing how). An advantage of this type of organization is it aligns with pedagogical strategies; each type of knowledge is associated with one or more types of learning (e.g. learning by doing versus learning by direct instruction). There are a number of knowledge typologies from different domains that could be applied to this task. The most relevant is perhaps Roland Müller and Katja Thoring's typology of design knowledge which identifies four forms of knowledge: Physical or Embodied Knowledge, Tacit or Neuronal Knowledge, Symbolic Knowledge (explicit, codified knowledge), and Scientific Models (knowledge represented as theories) (Müller & Thoring, 2010). Another is Lorin Anderson et al.'s typology of knowledge for use by educators, which is a revision of the relatively well-known Bloom's Taxonomy (Anderson, Krathwohl, & Bloom, 2005). This typology identifies four forms of knowledge; Factual Knowledge, Conceptual Knowledge, Procedural Knowledge and Metacognitive Knowledge. A third knowledge typology is by Victor Dörfler et al., from the field of knowledge management. Their typology includes five forms of knowledge; Knowing-That, Knowing-How, Knowing-Why, Knowing-What, and Knowing-If (V. Dörfler, Baracskai, Velencei, & Ackermann, 2008). A fourth typology is by Harry Collins, a sociologist who studies scientists. Collins describes the difference between Explicit (and explicable) Knowledge and Tacit Knowledge (relational, somatic and collective) (Collins, 2010).

These typologies are a promising tool for organizing the 13 forms of knowledge and skill related to visual communication; however, apart from the challenge of aligning their different conceptualizations or choosing the best one, the forms of knowledge and skill included in the list do not fall neatly into these categories. For example, *knowledge of visual design principles* has factual/explicit/declarative/knowing-that aspects as well as conceptual, procedural, knowing-why, knowing how and tacit aspects. One can *know* a design principle such as the principle of Unity in terms of being able to define it (declarative knowledge), but also in terms of being able to recognize its presence perhaps without being able to explain it (tacit knowledge) and in terms of being able to manifest it (know-how or procedural knowledge). For now, I have fallen back on organizing the forms of skill and knowledge based upon the aspects of the creation-manifestation-interpretation process they are aligned with (as shown in Figure 25), although future work may identify a way of leveraging these knowledge typologies for this purpose.

Another challenge in creating this list is that the many facets of creating effective science visuals, while often dramatically different from each other, are tightly intertwined and difficult to clearly separate. To avoid the problem of overlap, a candidate for inclusion was retained only if it could theoretically be acquired independently of the other forms of knowledge. For example, although learning about the audience's content knowledge would generally go hand in hand with learning about the visual conventions used for representing that knowledge, they are distinct forms of knowledge and one could theoretically study visual conventions without learning about a particular audience.

Forms of skill/knowledge for creating effective visuals

1. Knowledge of psychology-based guidelines
2. Knowledge of audience expertise
3. Knowledge of conventions
4. Knowledge of vision
5. Knowledge related to representation
6. Visual sensitivity
7. Visual design principles
8. Context knowledge
9. Knowledge of design strategies
10. Design thinking skills
11. Design repertoire
12. Self Awareness
13. Technical Skill

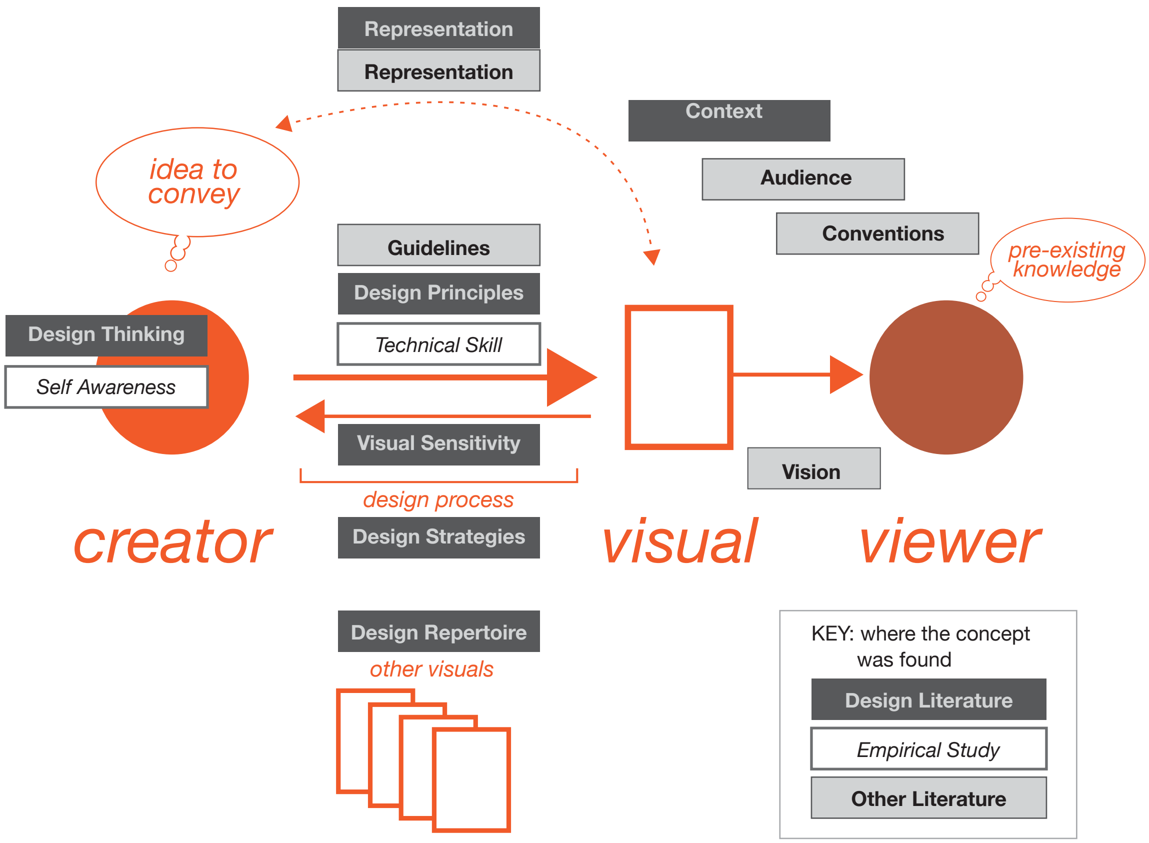


Figure 25: Knowledge and skills for creating effective visuals (identified in the literature and empirical study)

Below I describe each form of skill and knowledge included in the list. The sequence of presentation is based upon whether they were expressed in the *Effective Visuals* literature, the *Design and Design Education* literature or solely in the empirical study. I start with the themes identified in the *Effective Visuals* literature.

FORMS OF KNOWLEDGE/SKILL IDENTIFIED IN THE *EFFECTIVE VISUALS* LITERATURE

The five forms of knowledge and skill identified in the *Effective Visuals* literature are:

1. Knowledge of psychology-based guidelines
2. Knowledge of audience expertise
3. Knowledge of conventions
4. Knowledge of vision
5. Knowledge related to representation

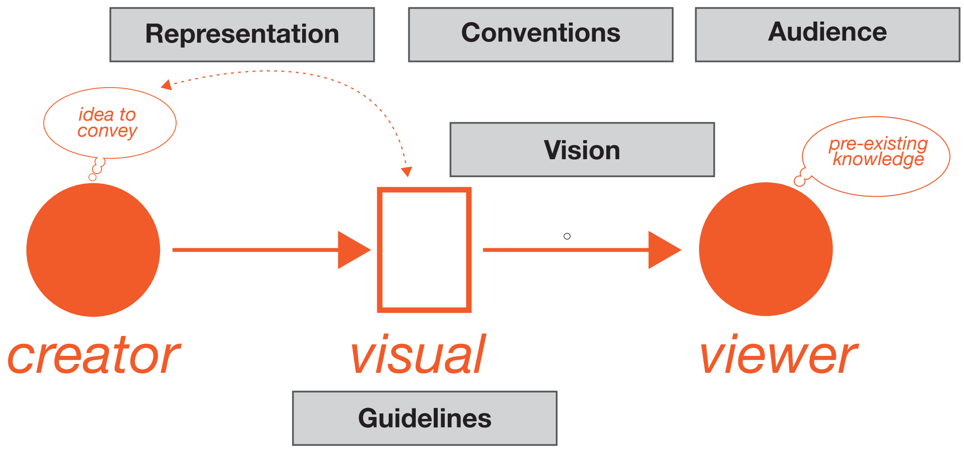


Figure 26: Five forms of knowledge identified in the Effective Visuals literature

Knowledge of psychology-based guidelines

This refers to guidelines for creating effective visuals that are based upon psychology research. The research they are based on may be complex, but the guidelines themselves are generally straightforward – they can be read and immediately applied (in contrast to visual design principles which I will refer to later). One example is from Richard Mayer's *Principles of Multimedia Design*: "People learn better when corresponding words and pictures are presented near rather than far from each other on the page or screen" (Mayer, 2009, p. 267). Another example is from Stephen Kosslyn's *Elements of Graph Design* "Inner grid lines should be relatively thin and light" (Kosslyn, 1994, p. 182). A third example is from Cynthia Brewer's *Guidelines for use of the perceptual dimensions of color for mapping and visualization*: "Generally, qualitative differences should be represented with colors that are different in hue with similar lightness" (Brewer, 1994b, p. 55).

From the empirical study

This was not a prominent theme in the students' comments, although one student who had taken the course mentioned that he appreciated learning psychology-based principles. (It is not entirely clear that the students made a distinction between psychology-based guidelines and design principles).

Knowledge of audience expertise, Knowledge of conventions

I have combined two themes here: *knowledge of audience expertise* and *knowledge of conventions* because they are so closely related, but I identify them as separate forms of knowledge because knowing how concepts are traditionally displayed is distinct from knowing whether the target audience is familiar with the particular tradition. These forms of knowledge are not explicitly discussed in the literature I reviewed, but are a logical extension of themes B7 (An effective visual evokes relevant knowledge/schemas) & B8 (An effective visual is aligned with the viewers' knowledge & skills). In order to create a visual that is well aligned with the viewer's knowledge and evokes that knowledge appropriately, one must know which aspects of the knowledge represented are new to the viewer and which are not, as well as what visual conventions they are familiar with, both in terms of the representational forms (e.g. notational conventions like the y-shape to represent an antibody , or more elaborate representations like the use of a stacked column to represent the stratigraphic layers of a geologic formation), and in terms of presentation features such as a conventional use of color or even a conventional layout.

From the empirical study

While this is an implicit theme in the *Effective Visuals* literature, it is an explicit theme in the comments by graduate students. It was the third most common theme in responses to the question "What skills/knowledge do you feel it takes to make successful science visuals?" (The two most common themes were "knowledge of software" and "knowledge of the science."). The following quote is representative:

> … and I guess the other end of understanding *your* topic is understanding your audience as well—who is this intended for, what's the purpose of it …Uh, so I would guess like, like who they are, what their—it kind of goes back to the presentation stuff, but...uh, what, what their, what knowledge they're coming in with. —Participant 3 (Rehabilitation Medicine), first interview

This next quote is a glimpse into the importance of being familiar with visual conventions that are about effective communication, but not simply about making the information comprehensible:

> In my last presentation somebody was like "you really should use these settings in ChemDraw. It will look much better and the people who will be at your first and second year exams are going to see this and think you don't know what you're doing." —Participant #4 (chemistry), first interview

The students also described the audience for their visuals, and these comments reveal breadth of audience types scientists may encounter and hint at the corresponding depth of audience knowledge they must acquire. For example, the comment below is from a student who works in an interdisciplinary area. It is in response to a follow-up question about how visual conventions for his audience (primarily biochemists) differ from visual conventions in his own field (physics):

> I feel like there's a bigger emphasis on physics so there's more reductionism and you're more likely to draw things by hand (…) So you're more likely to say like 'this is a ball' and it's moving some arrow, even if it's actually like a pineapple or something that's not technically ball shaped. But a lot of the biochemists, especially like the protein people...like do have access to a like a crystal structure (…) this very detailed, 3-dimensional image of the thing that you're studying (…) and they tend to slap that up even if you don't really know....like even if you don't really care about any of the structure. —Participant #13 (Biophysics) second interview

The last quote is from a student who has two distinct audiences and must vary her presentation depending upon the venue:

> I go to two separate types of conferences, both of which are fairly specialized for what they do. One of them, or one set of conferences is more ecology-based and tend to be heavy on the amphibian, herpetology side, so those people are generally right in step with what I'm doing, so they know where I'm coming from in a lot for ways, for any field research that I do… And then the other set of conferences I go to are toxicology conferences....for them I have to kind of take a different stance and present more of that chemistry stuff. —Participant #17 (Aquatic and fisher science), second interview

Knowledge of vision

Knowledge of vision refers to an understanding of how the eye works (e.g. how rods and cones in the retina are involved in color vision) and how visual information is processed (e.g. pre-attention awareness of patterns). The value of knowing how vision works is not a strong theme in the *Effective Visuals* literature, but I include it because there are some influential works on information visualization that use knowledge of vision and visual cognition phenomena as a basis for making design decisions. One is Colin Ware's *Information Visualization: Perception for Design*. Ware is a cognitive psychologist and computer scientist. He states in his preface that "Visualization can be approached in many ways. It can be studied in the art-school tradition of graphic design. It can be studied within computer graphics as an area concerned with the algorithms needed to display data. It can be studied as part of semiotics, the constructivist approach to symbol systems. These are valid approaches, but a scientific approach based on perception uniquely promises design rules that transcend the vagaries of design fashion, being based on the relatively stable structure of the human visual system" (Ware, 2000, p. xxii). Another important contribution is geographer Alan MacEachren's How Maps Work (2004). As its title suggests, his book is presented as an analysis rather than a set of proscriptive guidelines, but like Ware's book, it includes extensive information about the visual system as a substantial part of what the author refers to as a "scientific approach to improving map representation and design." In addition, courses on Information Visualization taught by computer scientists often include lectures on vision. In *Do We Need Formal Education in Visualization?,* Gitta Domik, a computer scientist includes "understanding vision, memory and perception" in her list of topics to be taught (Domik, 2000). The message in these works is that an understanding of how vision works will lead to better design.

From the empirical study

There were no comments made referring to knowledge of how vision works in the empirical study.

Knowledge related to representation

Knowledge related to representation refers to what one needs to know to devise or select an effective correspondence between an idea and its visual form. Aspects of representation include whether to use a literal or schematic illustration, and how to encode data or information attributes visually (e.g. with color, size, shape etc.). Representational knowledge also includes the relative strengths and weaknesses of verbal versus visual representations. Luc Pauwels, a professor of communication, identifies a complex array of factors involved in making representational choices which include the intended purpose of the visual, the nature of the referent, and the issues that arise in making decisions about, for example, how to best represent an entity that varies over time or from specimen to specimen with a single static representation (Pauwels, 2008).

From the empirical study

None of the interview participants talked about needing to have *knowledge related to representation*, yet over the course of the interviews, four participants mentioned that they were currently struggling with a representation challenge. Here is one example:

> So, I actually have quite complicated data that isn't easily visualized. So what we get... I'm an astronomer, and I study [neutral] hydrogen in other galaxies and when you get that data you have essentially a 3-dimensional data cube so you have spatial axes on the x & y axis and then along the third dimension you have velocity—the velocity that the gas is moving at. And so when you work with this data you can look at this data cube and watch how it changes from channel to channel (that's what they're called), but then if you actually want to convey your findings, you can't publish that data cube, you have to condense it down somehow. So that's, for me it's really, really important. —Participant #5 (Astronomy), first interview

In terms of the importance of this form of knowledge, it is noteworthy that even new scientists (doctoral students) find themselves in situations in which they cannot fall back on established display conventions but need to create new representations. Here is another example of the same issue:

> Up until about 4 or 5 years ago, all there would be would be just the 1 slice. So it was a lot simpler. And so now that..., you know the controversy is figuring out how to handle these multiple slices. (…) And so, because it's less established it's requiring more thought from me or more input about what I think is appropriate. —Participant #22 (Earth Sciences), second interview

Struggles with representation issues were also apparent in the comments students made in their course portfolios:

> When the goal is to show a large overall sequence of events, as is the case in variation 2, I have realized that a flow chart is much more clear and to the point than simply building more and more onto an already-busy diagram. —Participant #25 (Computer Science), Portfolio

Summary: forms of knowledge from the Effective Visuals literature

To summarize, the forms of knowledge and skill identified in the *Effective Visuals* literature are: knowledge of psychology-based guidelines, knowledge of the audience' level of expertise, familiarity with visual conventions, an understanding of how human vision works, and knowledge of visual representation strategies. Of these, only knowledge of the audience' level of expertise was well represented in the data from the empirical study.

FORMS OF KNOWLEDGE & SKILL FROM THE DESIGN LITERATURE

Visual communication design is a practice- rather than a research-oriented field. Its wisdom is captured more in the products of design, and in writings based on expertise and mastery, than academic research. There is however, a small body of academic literature produced by researchers who have studied designers, and it includes discussions of the skills and knowledge used in design. (Note that this literature is not specific to *visual communication* design, but applies to design in general, which includes disciplines such as architecture and industrial design). Another important source of insights into the knowledge and skill needed by visual communication designers is a thoughtful essay written in 1998 by Geoffry Fried and Douglass Scott, two experienced designers who have also worked as design educators (Fried & Scott, 1998). The essay is titled "The Common Core." It consists of three sections: "Who We Are", "What We Value" and "What We Teach" (the section I draw upon here).

The additional 6 forms of knowledge and skill that are mentioned in this literature are:

6. Visual sensitivity
7. Visual design principles
8. Context knowledge
9. Knowledge of design strategies
10. Design thinking skills
11. Design repertoire

Figure 27 shows these 6 forms of skill and knowledge as they relate to the creation and use of visuals. It also includes a 7th form: *Representation,* which is not included in the current list because it was introduced earlier (it is the only form of skill or knowledge that appeared in both bodies of literature).

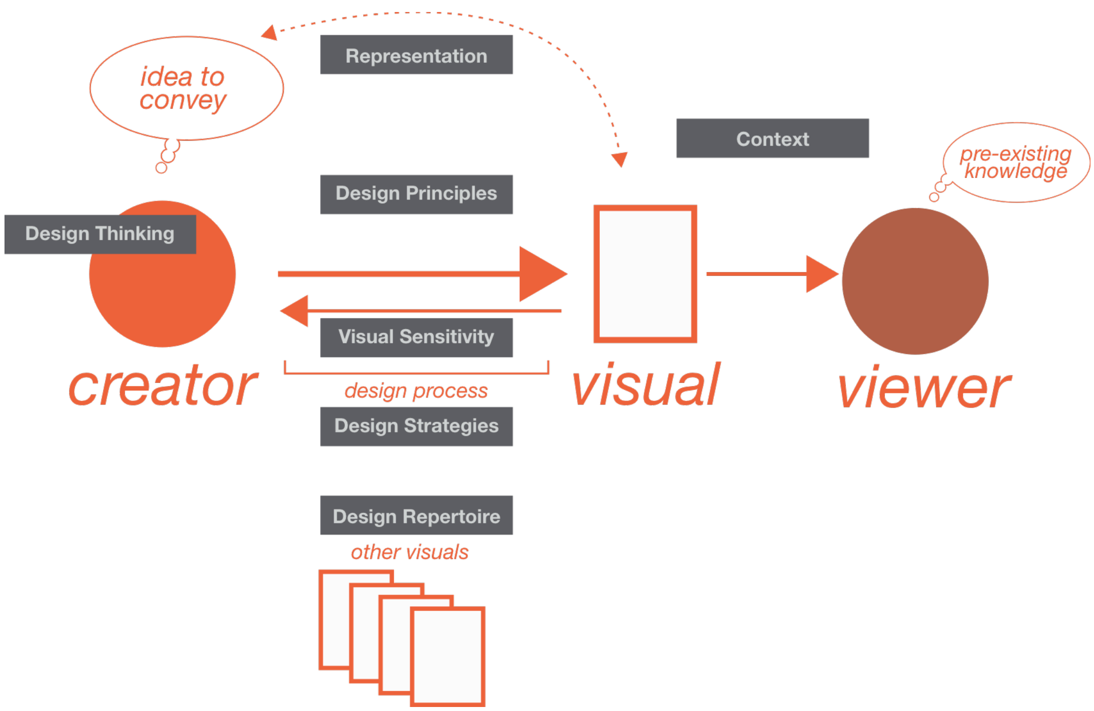
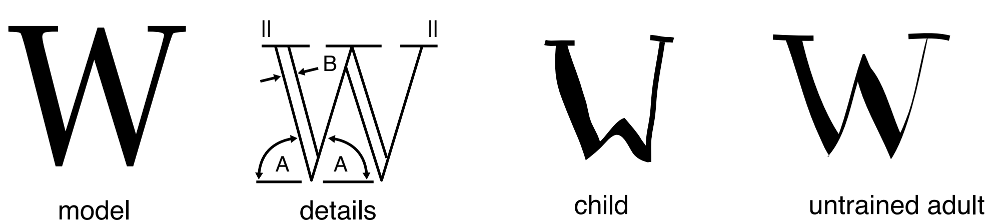


Figure 27: The 7 forms of skill and knowledge identified in the Design expertise & education literature

Visual sensitivity

The first form of skill identified in the *Design and Design Education* literature is visual sensitivity. Fried & Scott describe visual sensitivity as "an ability to see, differentiate, and recognize nuances of shape or form, placement, value, color, and space" (Fried & Scott, 1998, p. 174). Lois Hetland et al. list this as one of eight "Studio Habits of Mind." "Learning to attend to visual contexts more closely than ordinary 'looking' requires, and thereby to see things that otherwise might not be seen" (Hetland, Winner, Veenema, & Sheridan, 2007, p. 6). Peter Booker, an engineer, refers to a similar concept in his 1979 book on the history of engineering drawing in a chapter titled "The fundamental nature of drawing." He describes what a child or an untrained adult will typically produce when asked to replicate a letter "W":



He says that "To notice all these things one must have built up conscious concepts of angles, of parallelism, of equality, of straightness and so on." "With some drawing training, one might eventually analyse this letter as in [the "details" version] and so draw it properly. It is worth noting that, left on their own, very few persons ever reach the stage when they can properly analyse and so draw even one letter of the alphabet" (Booker, 1979, p. 9). In the context of science visuals, this would refer to skills such as the ability to notice that the choice of color scheme is unintentionally conveying the perception that some elements are more important than intended.

From the empirical study

There was some evidence of an emerging visual sensitivity in the comments by students who had taken the course on creating visuals; several referred to having a better awareness of visual qualities:

> As a critiquer, it was a good lesson in focusing on the presentation and getting wrapped up in the facts and content of the things that I really didn't understand. It was hard, but I was eventually able to step back and look for presentation rather than content. —Participant #7 (Rehabilitation medicine)

Several students who had not taken the course made comments reflecting a lack of visual sensitivity—referring to the ability to see that a design was effective or ineffective, but being unable to say why:

> It's just sometimes things look better to me, I can't say why." -Participant #5 (Astronomy), first interview. "It's easy to look at a graphic and say 'oh, that's terrible'. And it's easy to look at a graphic and say 'wow, that's a great looking figure', but the ground in between there is hazy. —Participant #9, (Atomic Physics), first interview.

Visual design principles

Visual Design Principles refer to a set of principles used in art as well as other visually-oriented design fields, such as interior design and industrial design and visual communication design. An example is the principle of Unity: "Unity exists in design when all elements are in agreement. Elements are made to look like they belong together, not as though they happened to be placed there randomly" (White, 2002, p. 57). Unlike the psychology-based principles described above, these principles are not straight-forward rules to follow, but require skill to implement – a type of skill Fried and Scott describe as the ability to use "nuances of shape or form, placement, value, color, and space and an ability to use those characteristics to create specific visual or physical relationships" (Fried & Scott, 1998, p. 174). Many design principles originate from art, and could be construed as being more important for aesthetics than function though there can be functional implications of aesthetic choices. For example, making elements look similar not only gives them a pleasing sense of harmony, but also conveys the message that they represented conceptually-related concepts.

From the empirical study

None of the interview participants made reference to knowing design skills as a form of knowledge needed to create effective visuals. However, when asked whether they were familiar with design principles, several said they were. One participant had an extensive art background; two said they followed design blogs and had some awareness as a result of that; four had family members who were artists or designers and they felt they had picked up some awareness as a result; one mentioned using ideas about composition that he had learned from photography courses. Just two mentioned learning about design principles during graduate school – one from a seminar on science communication and the other from 1-day workshop his lab group had created for themselves. One participant who had no exposure did seem nonetheless aware and interested:

> I hear all this cool stuff about, you know PowerPoints and where people's eyes go first and things like, I have no idea, it seems awesome. —Participant #11 (Atmospheric Sciences), first interview

Another participant who was clearly invested in making her visuals effective, made a comment that suggested a lack of awareness of design principles:

> In terms of what works visually or cognitively or whatever, that seems to be more trial and error and personal preference. —Participant #22 (Earth Sciences), second interview

Some design principles were introduced in the course and there were a handful of comments from the course material that referred to these principles to describe their designs. One example is the following quote:

> The visual unity of the figure could be enhanced if I could make all the small, grey boxes the same width -- perhaps exactly half the width of the large white boxes. —Participant #1 (Computer Scientist), portfolio

In summary, many students had a small amount of exposure to design principles from experiences unrelated to their scientific training, and there was modest evidence that students are receptive to learning these principles.

Context knowledge

Context knowledge refers to an ability to be aware of and accommodate the physical and psychological setting in which viewers will encounter a visual. Fried and Scott point out that “How things are interpreted is always a function of the context in which they are seen. What is useful in one situation may not be understood or appreciated in another…” and part of the job of a graphic designer is “…to know when a concept is appropriate to a specific situation or a particular medium” (Fried & Scott, 1998, p. 174).

From the empirical study

The idea that different visuals are appropriate in different contexts came up several times in the interviews. The students did not include it in their lists of skills or knowledge, but at other points in the interview a few referred to the difference between a visual for a conference presentation which had to be processed during the brief time it was projected on the screen, and a visual for a journal publication which had to fit into a narrow column and remain legible:

> …in conference presentations I do more, maybe cartoony sort of figures things that are maybe a bit more conceptual to just sort of peak/tweak their interest… in a conference you're, you see it for maybe 30 seconds and in a paper hopefully someone will sit there for a minute or a few minutes and sort of look at it. —Participant 10 (Civil Engineering), first interview

Knowledge of design strategies

Knowledge of design strategies refers to an awareness of strategies for eliciting and refining ideas. The nature of design as a creative process of constructing a solution as opposed to a logical or algorithmic procedure for deducing a solution comes up repeatedly in the design literature. Kees Dorst quotes architect Richard MacCormac, as saying "I don't think you can design anything just by absorbing information and then hoping to synthesize it into a solution. What you need to know about the problem only becomes apparent as you're trying to solve it" (Dorst, 2006, p. 55).

In terms of applying the value of design strategies to creating science visuals, the important conceptual shift is to see the creation of a science visual as a design process—a process in which the creation process calls for skillful decision making to balance competing goals—rather than an algorithmic or rule-based process in which creating a visual is a matter of knowing the appropriate steps to follow for the given data and setting.

Fried & Scott refer to the importance of knowing "techniques for problem definition, generation and evaluation of ideas" (1998, p. 174). One such technique, described by designer Kees Dorst is to develop multiple solutions simultaneous: "Designers and design theorists agree that it is important to always develop several design options in parallel (Dorst, 2006, p. 57). David Marples, an engineering professor explains why this particular strategy is important: "The nature of the problem can only he found by examining it through proposed solutions and it seems likely that its examination through one, and only one proposal gives a very biased view. It seems probable that at least two radically different solutions need to be attempted in order to get, through comparisons of sub-problems, a clear picture of the 'real nature' of the problem" (Marples, 1961, p. 64).

Design thinking skills

Design thinking skills refer to ways of thinking about design problems that are either unique to designers or highly refined in designers. This is a recurrent theme in the literature, but not one that is consistently described or precisely defined—perhaps because it is a largely tacit form of knowledge which, by definition, means it is difficult to express in words: "What designers know about their own problem-solving processes remains largely tacit knowledge—i.e. they know it in the same way that a skilled person 'knows' how to perform that skill. They find it difficult to externalise their knowledge" (Cross, 2006, p. 9).

I will give three additional examples of this concept as it is expressed in the literature. The first is from Roland Müller, an information scientist, and Katja Thoring, an industrial designer and design educator. In their typology of design knowledge they include the ability to interpret and filter incoming information in a design-oriented way: "Designers should be able to look at the world differently: they need to see things (problems, opportunities, etc.) that other people don't notice" (Müller & Thoring, 2010, p. 3). The second is from Bryan Lawson, an architect and educator and Kees Dorst, an industrial design and design researcher, who write about design expertise and how design thinking skills give designers "the ability to think along parallel lines, deliberately maintain a sense of ambiguity and uncertainty and not to get too concerned to get to a single answer too quickly" (2009, p. 60). The third is from Donald Schon, a sociologist who studied design education, describing the unique way in which designers approach design challenges: "When practitioners succeed in converting a problematic situation to a well-formed problem, or in resolving a conflict over the proper framing of a practitioner's role in a situation, they engage in a kind of inquiry which cannot be subsumed under a model of technical problem-solving. Rather, it is through the work of naming and framing that the exercise of technical rationality becomes possible" (Schon, 1985, p. 16).

From the empirical study

References to design strategies are all but absent in the comments by students before taking the course (although several referred to the need to take time and care—an allusion to the creation process). Design strategies including iteration, multiple versions and critique were introduced in the summer course and students responded positively to them.

> I really like the idea of design revisions. I think that was a really valuable thing. (…) especially when you kind of, yeah, just sit there and 'I have to make this look different. It may not be better, it just has to be different.' And then you uncover just things randomly that way. It starts out as kind of a yeah, really forced thing, but then sometimes like 'oh, I really like this part.' So I think is really crucial. —Participant #8 (Computer Science), second interview

Design repertoire

A design repertoire refers to a memory bank of successful designs (effective science visuals) and design experiences to call upon – the idea that one does not start designing from scratch, but draws upon a memory not just of principles and concepts, but instantiations of those principles and concepts. Bryan Lawson and Kees Dorst argue that "Learning design does not just involve skill acquisition, it also involves the learning of declarative knowledge, and the building up of a set of experiences that can be directly used in new projects. These experiences become a repertoire of earlier solutions that can be applied by the designer" (Lawson & Dorst, 2009, p. 100). Nigel Cross, a designer and design researcher who writes about how designers think and work makes a similar point: "Something that distinguishes experts from novices is that the experts have been exposed to a large number of examples of the problems and solutions that occur in their domain" (Cross, 2011, p. 146). And later: "The novice designer also needs exposure to many good examples of expert work in the domain, and needs to learn to perceive and retain these examples, or precedents, in terms of the underlying schemata or organizing principles" (Cross, 2011, p. 147).

From the empirical study

In the interviews, 18 of the 22 participants referred to the value of having had extensive exposure to visuals as graduate students and using the visuals they saw as models to either emulate or avoid.

> …a lot of experience with what makes a good graph and what makes a bad graph. Which I guess is a way that you learn a lot. Just by reading papers with bad graphs and saying "wow, I wish they had done this differently because it's really hard to read, I have no idea what's going on." —Participant 13 (Biophysics), first interview

The effectiveness of this approach is limited, of course, by the quality of the visuals they are exposed to and their ability to make good judgments about which aspects of a visual make it effective.

> I think in that sense, the literature is a big, sort of the self-...the circular thing. Someone makes a plot, and then everyone makes that plot then everybody else makes it. —Participant 11 (Earth sciences), first interview

To summarize, the additional forms of knowledge and skill that are identified in the *Design and Design Education* literature include visual sensitivity, visual design principles, context knowledge, knowledge of design strategies, design thinking skills and a design repertoire.

Knowledge related to representation

This is the one form of knowledge that is described or alluded to in both the *Effective Visuals* literature and the *Design and Design Education* literature. I defined this form of knowledge above as referring to "what one needs to know to devise or select an effective correspondence between an idea and its visual form." Fried & Scott refer to "visual ideas" "communicated through the organization of the material (structure, emphasis, and hierarchy) and through association with known ideas (symbols, signs, metaphors, and visual language)" (Fried & Scott, 1998, p. 174). While recognizably the same concept, the expression of this idea in the *Effective Visuals* literature has a distinctly different flavor than its expression in the design literature. In the *Effective Visuals* literature it is presented as a more straight-forward, discrete, rule-based or algorithmic concept—an example is Cleveland's recommendations for choosing an effective graph type based upon the ease of the perceptual tasks (Cleveland & McGill, 1984). In Fried & Scott's description it is presented as being more nuanced and contingent—involving the interactions of multiple aspects of the design simultaneously.

FORMS OF KNOWLEDGE & SKILL FROM THE EMPIRICAL STUDY

Two additional themes emerged from the empirical research: "self awareness" and "technical knowledge."

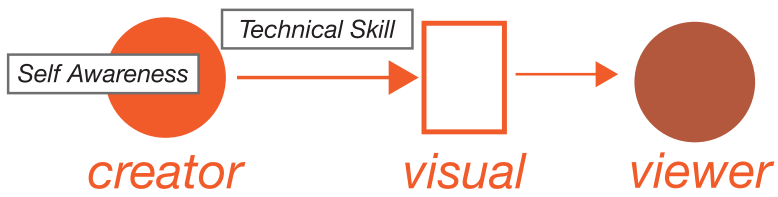


Figure 28: knowledge and skills identified in the empirical study

Self awareness

Self awareness refers to recognizing how one's own biases and tendencies influence the visuals one produces. This is perhaps alluded to in Schon's writings about reflective practice, but it is not a clear theme in the literature. On the other hand, it had enough of a presence in the empirical study to warrant inclusion. Four interview participants made comments related to self-awareness. All four made those comments after taking the course, and the comments themselves suggest that it was the experiences of the course that led to the insights. One student referred to noticing that he was too attached to a design to make changes his classmates suggested; another referred to recognizing, after experiencing the value of critique, that he had previously been resistant to feedback; a third noticed that her preference for creating *clever*, rather than simple visuals, was problematic; the fourth referred to recognizing, as a consequence of being asked to create parallel designs, that he had been narrow in his thinking.

Knowledge of the technical tools

Knowledge of the technical tools means the ability to use available software to create visuals. The participants reported using an average of 3.8 different software applications for creating their visuals (the minimum was 1 and maximum 7). It is not particularly surprising that neither the *Design Literature* nor the *Effective Visuals Literature* emphasize the importance of technical skills for creating visuals; it is stating the obvious and is not of particular interest to psychologists or designers and yet the participants' comments suggest that lack of technical skill can be a real barrier to creating effective visuals:

> So [even] to have the technical skills to just make it so and um, get what you have in your head onto the page. Uh, that's still something that I think a lot of scientists wrestle with; they just don't know how to do it. —Participant #9, (Atomic Physics), second interview

SUMMARY

The 13 forms of knowledge and skill are all shown (again) in Figure 29:

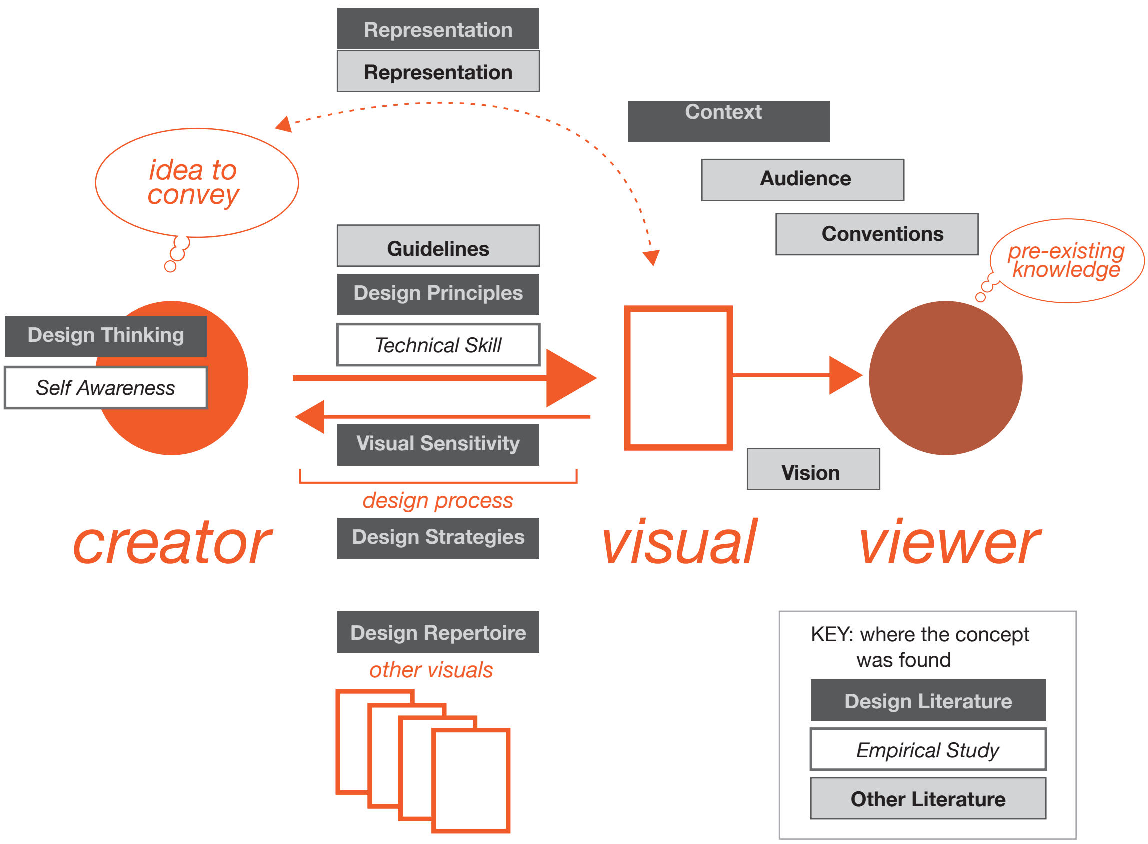


Figure 29: Knowledge and skills for creating effective visuals (identified in the literature and empirical study)

Discussion: differences in perspective

These forms of skill and knowledge are presented in 3 clusters – those that came from the research world of cognitive educational psychology, those that came from the experience of graduate-level scientists and those that come from the practice-based world of design. As the diagram shows, there is very little overlap between the three clusters – suggesting that designers, psychologists and graduate students have difference perspectives on the skills and knowledge required for creating effective designs. There are a number of ways to view this split. One is to see it as reflecting three distinct approaches to creating visuals – approaches that could be labeled an analytical knowledge-based approach (psychology), a common-sense approach (graduate students) or an artistic, skill-based approach (design). Perhaps these different approaches work best for different individuals (e.g. those with a more "scientific" bent versus those with a more "artistic" bent). Perhaps these different approaches work best for different types of visuals (e.g. those with a more purely "informational" intent versus those with a more "engaging, persuasion" intent). Another way to view the split is as a reflection of three skillsets that all contribute and should ideally be combined. This is suggested by designers who argue for the value of adopting theories and strategies from outside the traditional realm of design (Frascara, Meurer, van Toorn, Winkler, & Strickler, 1997; P. Storkerson, 2004?) and by those from more analytical, scientific traditions who argue for the value of adopting the strategies of design (Robinson, 1952; Rushmeier, Dykes, Dill, & Yoon, 2007; Wolf, Rode, Sussman, & Kellogg, 2006).

CHAPTER 9: HOW COMPETENCE IN VISUAL COMMUNICATION IS DEVELOPED

If we define competence in visual communication as a set of skills and knowledge, then it is useful to understand how people develop those forms of skill and knowledge. In this chapter, I present the findings related to the research question "What forms of learning produce the skills and knowledge that constitute competence in visual communication?" These findings come primarily from the design literature, which examines how formal visual design curricula are structured, with a small contribution from the empirical study – from students' comments about how they have learned to create visuals as well as their response to the pedagogical strategies used in the course.

The Literature reviewed

As mentioned in chapter 2, the topic *how scientists acquire competence in visual communication* is not actively and explicitly addressed in the published literature. The main source of knowledge I will draw on, therefore, is the design literature. But before looking at that literature, I will acknowledge a cluster of articles discussing the value of two visual traditions: biology drawings and engineering drafting. I will start with two examples from biology. The first is by Neal Lerner who runs an academic writing center. He describes the work of "pre-eminent naturalist" Louis Agassiz, a Harvard Professor of Zoology in the mid-19th century who introduced the use of drawing and reflection in the classroom to teach his students the mental discipline of observation (Lerner, 2007). The second is by Sarah deRijcke, a psychologist who analyzed how biologist Santiago Ramón y Cajal used his drawing skills to develop and communicate insights into nerve tissues in the late 1800s (when photographic techniques were also available). She reports that Cajal considered drawing to be by far the best rendition method in large part because it disciplines the scientist's eye (reminiscent of the concept of *visual sensitivity* described in the previous chapter) (de Rijcke, 2008). In the engineering realm, Peter Booker describes the value of teaching drafting skills to engineers: "In its narrowest sense engineering drawing is a language used for communication. However, languages in general are not only useful for communication; they play an inherent part in our very thinking, for we tend to think in terms of the languages we know. Drawing is of this nature, and he who can draw can think of, and deal with, many things and problems which another man cannot" (Booker, 1979, p. xv). These topics (the value of drawing to hone observation skills and as a language for communication) are peripheral to the main themes of this dissertation, but they do suggest additional motivation for teaching these skills, and they are aligned with Theme A6: A desired impact of science visuals is to build visual spatial thinking skills. Sheryl Sorby, an engineering instructor has conducted research on the importance of visual-spatial skills in the success of engineering students has demonstrated success using sketching to improve those skills (Sorby, 2009).

Next I turn to the more directly relevant body of literature about learning to communicate visually that comes from design educators.

DESIGN PEDAGOGY TRADITIONS

Dietmar Winkler, a professor emeritus of design describes how design programs in the United States and throughout the world generally follow the educational model established by the Bauhaus – a crafts and fine arts school that operated in Germany from 1919 to 1933 (Winkler, 1997). Characteristic features of this model include:

1. *Learning by doing*: Students are typically given a design assignment in the form of a "design brief" in which the design challenge is described and they learn to design by actually trying to design.
2. *Exposure to others*: Design work happens in a studio space in which students work alongside each other and are exposed to each others' process.

3. *Critique*: Students are frequently asked to present their work and receive critical commentary from the instructor and peers.

WHY IS STUDIO LEARNING APPROPRIATE FOR DESIGN?

In his 1985 book "The design studio: An exploration of its traditions and potentials," Donald Schon, explains why this form of pedagogy is so appropriate as "a setting for the acquisition of a competence to perform" (in this case to perform as a designer, but he makes the case that this teaching methodology should be expanded to other practice-based areas such as medicine) (Schon, 1985). A significant part of his argument is that much of what a designer knows can only be learned through experience and active engagement. Schon talks about the dilemma of design education being that "the student cannot initially understand what he needs to learn; on the other hand, he can only learn it by educating himself, and he can only educate himself by beginning to do it" (Schon, 1985, p. 57), and "His instructor cannot tell him what he needs to know, even if he has words for it, because the student would not understand him. The student is expected to find out for himself, to learn by doing. The studio seems to rest on the assumption that it is only in this way that he can learn" (Schon, 1985, p. 56). Belkis Uluoglu, an architect who studies design makes a similar point "If it was merely an activity, based on certain skills, then it could be taught by instruction. But we know that it also requires reasoning, which strips it from being merely an action, and takes it to another level where it is now considered as praxis(Uluoglu, 2000, p. 34). "…design is not merely the rational activity of the mind, but it also requires, in an inseparable manner, the skillful activity of the body (hands) and intuitive feelings of the soul" (Uluoglu, 2000, p. 35).

CRITICISMS OF STUDIO-BASED LEARNING

Despite the broad acceptance and practice of studio-based learning, there are voices that are critical of it, and they seem important to acknowledge. Dietmar Winkler, a design professor quoted previously, argues that the current traditions of design education are a result of the inertia of tradition as much as the perpetuation of successful strategies. He sees current design education as focusing on visualization skill, but missing out on the importance of teaching about the psychology and sociology concepts that help us understand communication. He recommends that "Through major curricular reforms, graphic designers and typographers must understand the full complexities of language, perception and human and social behaviour, not just in cursory ways via survey or introductory courses. They must be as comfortable with social and behavioural science as with literature and philosophy" (Winkler, 1997, p. 133). Peter Storkerson, who has both a Master of Fine Arts and a PhD in design, also recommends that graphic design education incorporate more traditionally academic forms of expertise. He points out that "Particularly in the United States, the large majority of graphic design programs are within larger visual fine art departments or schools of art within universities. The design/fine art institutional relationship has steered graphic design education toward the academic fine arts pedagogy and culture, which itself is studio based and non-academic" (Peter Storkerson, 2010, p. 9). He suggests that graphic designers would benefit from including more traditionally academic forms of knowledge and research. "How much more effective and persuasive would graphic designers be if they made a habit of testing and measuring to optimize their designs and back-up their claims" (p. 10). He argues that semiotics should be taught to designers but feels that the culture of design education makes that difficult: "the cultures of graphic design practice and education are themselves barriers to the understanding, acceptance and development of a semiotics that is useful to design" (p. 33).

There are also concerns that the studio approach is ineffective for some students. Arlene Oak, who has degrees in design and art as well as a PhD in social psychology, points out the potential for studio education to fail to serve less advanced students: "The very nature of the critique as ephemeral, face-to-face conversational assessment, with its explicit and implicit levels of information helps to promote a situation whereby those who already roughly comprehend the demands of design and design education, end up further comprehending, while those who do not easily understand, or who are not engaged or confident enough to enquire, are left further behind. In this way, the manner in which the language of the crit [critique] is managed assists in making it more likely that a particular type of person will suit the category of "professional designer"(Oak, 2000, p. 93).

What is perhaps most relevant in this criticism is that it suggests the form of education that can work so well to produce excellent designers may have limitations and may or may not be the most effective or the most feasible form of education for some audiences. Rudolf Arnheim, a perceptual psychologist makes an intriguing comment about communicating art concepts to scientists in the preface to the 1974 version of his classic work "Art and Visual Perception." "Much of what I had described derived from a few basic principles, but this derivation was not always made explicit in the text, nor were the principles themselves spelled out with sufficient emphasis. This style was not averse to the mentality of artists and art students who fastened on the visual specifics and caught the general sense pervading the whole. But even they, I came to feel, would be better served by a more unified organization. And certainly I could do better by the scientists and thinkers who preferred something more systematic" (Arnheim, 1974, p. ix). As I describe later in this chapter, the evidence from the response of students to critique in the course on science graphics suggests that scientists can respond positively to this form of teaching.

LEARNING/TEACHING STRATEGIES INHERENT IN STUDIO-BASED INSTRUCTION

Potential limitations aside, the widespread use of studio-based instruction and the skilled designers who emerge from programs that use this form of instruction provide evidence that it *is* effective for many. A handful of researchers have attempted to understand and explain just *how* this model supports learning. These include Donald Schon, in his 1985 book referenced above (*The Design Studio: An Exploration of its Traditions and Potentials*); *Studio Thinking: the Real Benefits of Visual Arts Education* by Lois Hetland, Ellen Winner, Shirley Veenema, and Kimberly Sheridan, a team of psychologists and art educators (2007); *Critiquing Critiques: A Genre Analysis of Feedback Across Novice to Expert Design Studios* by Deanna Dannels & Kelly Martin (2008), both professors of communication, and *Design knowledge communicated in studio critiques* by Belkis Uluoglu, professor of architecture (2000). From these fours sources, I have identified 7 forms of learning experience embedded in studio-based instruction:

1. *Direct instruction:* learning how to design through explanation, e.g. lectures, and by being told explicitly, what to do next
2. *Direct feedback:* hearing responses to one's own designs
3. *Exchanging ideas:* seeing and hearing about how others have approached a design problem as well as showing or describing one's own approach
4. *Expert modeling:* being exposed to the thought process of experts as they design or analyze designs
5. *Encouragement to experiment:* experiencing an environment in which one is rewarded and not punished for trying out innovative, but potentially unsuccessful strategies
6. *Exposure to design strategies:* being guided to utilize design strategies in one's own work
7. *Exposure to designs:* seeing many examples of designs (ideally with reflective awareness of how they successfully address design problems)

Direct instruction

Direct instruction refers to being told how to design, whether in the form of a lecture or reading on how to design, or in the form of a recommendation about what step to take next. While both Schon and Uluoglu make the point that much of design *cannot* be taught in this way, they do refer to some use of direct instruction—Uluoglu refers to presenting knowledge in the form of "lectures, speeches and written documents introduced by the SM (studio master) that cover both descriptive and normative declarations about architecture and design (Uluoglu, 2000, p. 40). In Schon's description of how a studio master helps a student he includes forms of direct instruction: "he may tell the student something about designing, general descriptions, specific instructions (…) suggesting that the student try various things (Schon, 1985, p. 63). Dannels & Martin found that 9% of critique comments were direct recommendations about a particular aspects of the design (2008).

Direct feedback

Direct feedback refers to receiving comments about one's own designs from peers or instructors – that help the designer to see how the design is perceived by others. Ululoglu identifies this as one of two purposes of critique, "The critiques are thought to serve two purposes; one is to communicate with the individual student and live in his/her world, *the other is to bring the student face to face with others' ideas to see each other's worlds.* (Uluoglu, 2000, p. 54, emphasis added). Dannels & Martin makes a similar point: "A second educational goal reflected in the feedback types was to facilitate a viewer-based (or audience-based) mind-set. Critics modeled this kind of mind-set as they either restated how they saw the design (interpretation), gave their spontaneous reactions about what the design sparked in their mind (free association), or compared the design to other people's work or designs (comparison)" (Dannels & Martin, 2008, p. 150).

Exchanging ideas

Exchanging ideas refers to both expressing one's own ideas and being exposed to others'. Lois Hetland et al. make several comments along these lines: "When students see the range of ways their classmates have approached an assignment, they begin to envision possibilities outside their usual habits" (Hetland et al., 2007, p. 27). "Students gain insight about their own artmaking by verbalizing thoughts about their own work, and by hearing how others talk about their work" (p. 28). "Even without direction, as students look at and discuss each other's work, they envision different possibilities for how the work could look" (p. 103). Dannels & Martin found that 18.3% of critique comments involved sharing ideas—they "often took the form of what-if questions that served to help the student imagine other possibilities for their design product" (Dannels & Martin, 2008, p. 144).

Expert modeling

Expert modeling refers to hearing a skilled designer verbalize his/her thought process while engaging in a design process or while analyzing a design. Schon describes a scenario demonstrating this method of teaching during a critique session: "A great deal of what Quist [teacher] does in his dialogue with Petra [student] consists not in 'telling' but in showing. Starting with the givens of her design situation, and the big problems she has described, he gives her a demonstration of a version of the sort of design process she has already tried (stutteringly, as Quist says) to carry out" (Schon, 1985, p. 71). "Quist listens to her 'big problems' and then takes over, providing a master demonstration of a process similar to the one Petra is supposed to be carrying out" (Schon, 1985). Hetland talks about helping students learn observation skills through modeling (in this case modeling an analysis of artwork, but the same would apply to the analysis of a design): "Teachers model how they want students to look at and think about artworks. They often talk aloud through their thought process as they view a work" (Hetland et al., 2007, p. 28).

Encouragement to experiment

Encouragement to experiment refers to creating an atmosphere in which students learn to give themselves permission to take creative risks. Hetland says "The product is not the only thing that matters in assessment—students are praised for stretching beyond their usual style or habits of working, even if the resulting artwork is not particularly successful" (Hetland et al., 2007, p. 28). Similarly, Dannels notes that some of the critique comments seem to have the intent of encouraging students to take initiative: "perhaps one goal of design education in this context was to create independent thinkers. Several types of feedback focused on sparking independent thinking" (Dannels & Martin, 2008, p. 148 & 150).

Exposure to design strategies

Exposure to design strategies refers to experiencing the value of design process strategies (such as creating parallel designs or using critique to generate new ideas). Uluoglu and Dannels both talk about how the expert designer can guide students through the design process. "The role of the SM [Studio Master] is basically to control and manipulate the design process in the studio, where s/he determines the capacity of the student, plans the use of time, oversees dead-end streets in student's work and motivates the student towards new outlets, and carries the work to further stages" (Uluoglu, 2000, p. 40). Dannels found that 20.8% of critique comments made statements or asked questions about the student's design approach or process" (Dannels & Martin, 2008).

Exposure to a wide array of designs

Exposure to designs refers to encounters with finished designs that embody design principles and design knowledge in order to accumulate an internal repertoire of solutions. Uluoglu cites this as one of the goals of the studio master "…the SM should help the student to increase and deepen his/her theoretical, visual, and experiential accumulations" (Uluoglu, 2000, p. 56). This is well-aligned with the concept that some forms of design knowledge reside in and are conveyed via the designed objects themselves. This is mentioned by several authors writing about the nature of design knowledge (Cross, 2006; Müller & Thoring, 2010; van Aken, 2005). In contrast to explicit knowledge, which is built up through listening and reading, and tacit knowledge, which is built up through personal experience, object knowledge can be acquired by using and reflecting on designed object (Cross, 2006) or by re-engineering the designed objects (Müller & Thoring, 2010).

PARALLELS BETWEEN GRADUATE SCHOOL AND DESIGN EDUCATION

There are parallels between design education and the way graduate students learn to create visuals. Like design students, graduate students are presented with the need to create visuals, and then proceed to figure out how to do so. Like design students, graduate students are exposed to other's visuals and learn by example. Like design students, graduate students receive feedback on their designs from peers and mentors. In terms of the three elements of the studio model, the only element not present is the studio itself – the environment that exposes them to each other's process, although the lab setting might have some of the characteristics of the studio setting as well.

But while the structural elements are present, there is a major missing element, which is the guidance of an expert designer. Students receive feedback from their peers and advisors, giving them a chance to see how others perceive their designs, but the feedback is not the feedback of an expert skillfully crafted to guide learning, nor the feedback of students who have learned to model an expert's feedback. Graduate students have extensive exposure to science visuals and, as their comments suggest, they see what confuses them and try to avoid those mistakes, but they do not have the benefit of a skilled designer who can point out the more subtle characteristics of the design that make it unsuccessful or successful. Graduate students have the advantage of having opportunities to create real designs – designs that will actually be used to communicate to other scientists, although these opportunities are not carefully selected by an expert in design education to progressively challenge them in in a way that aids the development of skills.

Figure 30 lists the types of learning experiences described in the design literature on the left and indicates which of these elements are present or absent (gray text) in graduate school, on the right. The tildes indicate experiences that the empirical study suggest are either minimally present or present for some, but not all graduate students. I have added one additional element to the list of learning experiences graduate students experience, which is *exposure to the audience*. In a traditional design education, students learn from their peers and instructors, but do not necessarily have extensive contact with the target audience for their designs, while graduate students have extensive exposure to their audience at professional gatherings and even in their own labs. The following quote describes the type of encounter graduate students have that helps them develop a sense of their audience:

> (…) It really was like the first conference. People were asking me questions and I, you know, you kind of got the feel...like I, I assumed, you know I was a first year grad student, I had a whole complex that like 'oh yeah, of course everyone knows what's going on.' I have been working on this and all these people are smart, you know, established professors and so I kind of like went into some spiel and people started asking questions that made it obvious that they had no idea what the hell I was talking about. So had to back up a couple steps. — Participant #13 (Biophysics), second interview

Types of Teaching in Design	Types of Teaching in Graduate School
Direct feedback	Direct feedback
Exposure to repertoire of designs	Exposure to repertoire of designs
Exposure to audience	Exposure to audience
Sharing ideas	~Sharing ideas
Direct instruction	~Direct instruction
Encouragement to experiment	~Encouragement to experiment
Expert modeling	Expert modeling
Exposure to design strategies	Exposure to design strategies

Figure 30: Parallels between design teaching strategies and how science students typically learn to create visuals. Gray text indicates learning experiences that are not generally part of graduate level science education and tildes indicate learning experiences that are either minimally part of graduate level science education, or present for some students, but not others.

INSIGHTS FROM STUDENTS' RESPONSES TO THE PROBE

As described in chapter 4, the course introduced pedagogical strategies used in traditional design education, including exposure to design strategies such as creating parallel versions of a design and going through several iterative cycles, direct instruction in design principles, design feedback from an expert and peers, and opportunities to share ideas. We can see evidence in some of the comments from students that these pedagogical strategies were well received and experienced as helpful. This first comment is about appreciating the value of creating multiple versions:

> I think that was a really valuable thing to force iterations…It starts out as kind of a yeah, really forced thing, but then sometimes like 'oh, I really like this part.' So I think it is really crucial. —Participant #8 (Computer Science & Engineering), second interview

This second comment is about the value of critique:

> What I have learned in this course is that it's, um, not always guaranteed that other people will understand the message despite your best intentions. Um, it's something I have really learned, the power of feedback through the design process. I think in the past I had this sort of smug like oh, it makes sense to me, I'm pretty sure it would make sense to this audience. It's good, it's a final product and in reality, that's not how it works, you need to give it to somebody and ask them what they see here, what makes sense and what doesn't. —Participant #10 (Civil Engineering), second interview

Another student contrasted the feedback received in the course with feedback received from peers in the past:

> The feedback that we give each other usually in the group setting is always like 'this thing is hard for me to understand'. And maybe it comes with a 'if you changed this, it would be

> easier for me to understand.' It's this reactive readerly kind of critique. Whereas in this class, we learned to apply certain techniques and like follow certain rules… I can just say like 'uh, this, you didn't follow this rule very well' and that's different and helpful in a different way. —Participant #1 (Computer science), second interview

The comments were generally positive, although one student expressed discouragement because he could not come up with a substantially different design concept. This is reminiscent of the criticism that design pedagogy can leave some students behind:

> That was the other thing that I found really difficult. Um, is to create...to create one version was, was alright. And I understand why you want to create multiple versions. But it was just one of those things that...it, given the time frame again, you're like...I just my brain doesn't think that fast in terms of okay, what else could I possibly do with this. I don't know. This is, this is what I feel is the best, why would I create something else just for the sake of creating something else right now and I can't even think of how to create something else. —Participant #7 (Rehabilitation Science), second interview

SUMMARY

Visual Communication Design in the US is generally taught using the studio method, which consists of learning by doing in a studio setting with feedback and instruction provided via critique sessions. Within this structure, teaching happens in the 7 ways shown in Figure 31: direct instruction, direct feedback, exchanging ideas, expert modeling, encouragement to experiment, and exposure to design strategies. Themes that came from the *Design and Design Education* literature are in black boxes while themes that came from the empirical study are in white boxes. Those with a dotted outline were either minimally present in the interviewed students' experience, or present for some, but not for others. Many aspects of the studio method have parallels in graduate education where students learn by doing, and receive feedback about their work from instructors and peers. In addition, graduate students have ample opportunity to learn about their audience through exposure to them so this has been included in the diagram as an 8th teaching strategy. An important missing element in the graduate experience is the presence of a design expert to act as a guide and to model design behaviors.

The literature about design education raises some concerns—that some useful skills and knowledge are not typically taught to designers, and that this form of teaching may not be a good fit for all students. The course was an opportunity to test this to some degree—to see how graduate science students would respond to critique and other design pedagogy strategies. The response from the students suggests that design pedagogy can indeed be successfully used with graduate science students.

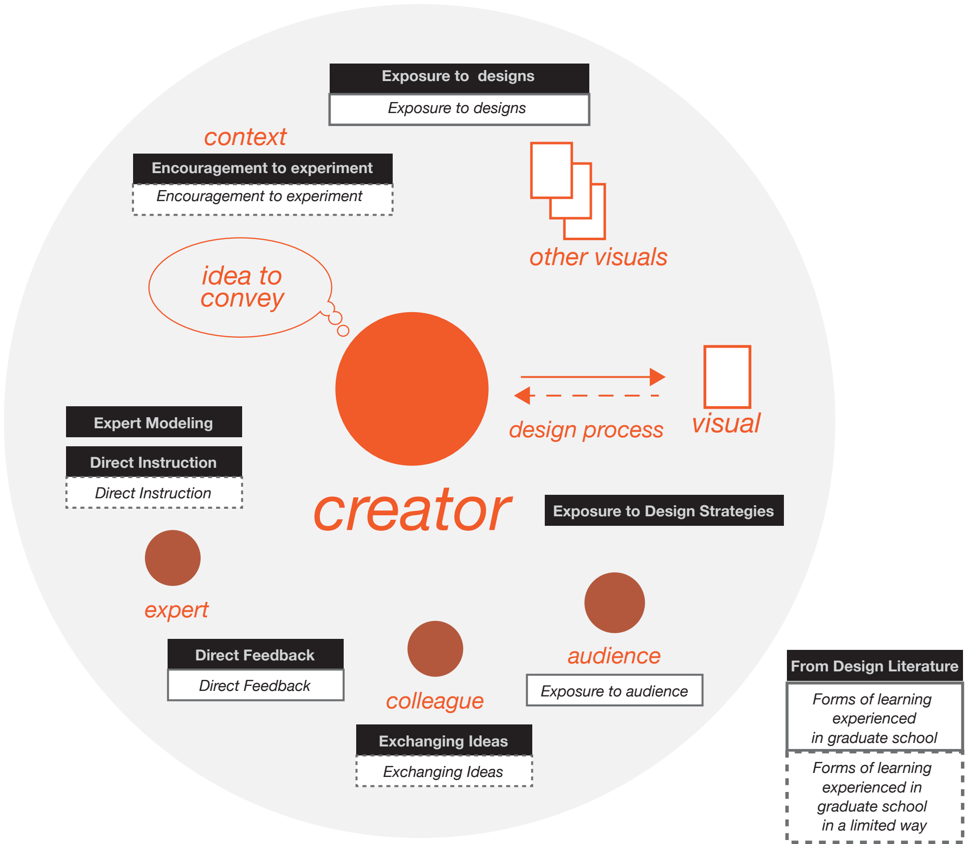


Figure 31: The 8 types of learning experiences identified in the literature and the empirical study

CHAPTER 10: CONCEPTUAL FRAMEWORK

As explained in chapter 4, a major goal of the analytic work for this dissertation was to produce a conceptual framework for *developing competence in visual communication*. That framework is presented in Figure 32 (which spans the next 4 pages). The four large gray circles represent the four aspects of *competence in visual communication*. Within each circle is a diagram indicating which player(s) in the creator-visual-viewer trio are most emphasized and showing how the themes relate to the players. For example, the *Learning Experiences* circle focuses on the creator (the one who is learning), while the *Impacts* circle focuses on the viewer (the one being impacted). The themes in the text boxes are shaded to indicate whether they were drawn from the empirical study (white boxes), the *Design Expertise & Education* literature (black boxes), or the *Science Visuals/Effective Visuals* literature (gray boxes). After the pages containing the framework, I provide a tour through each circle.

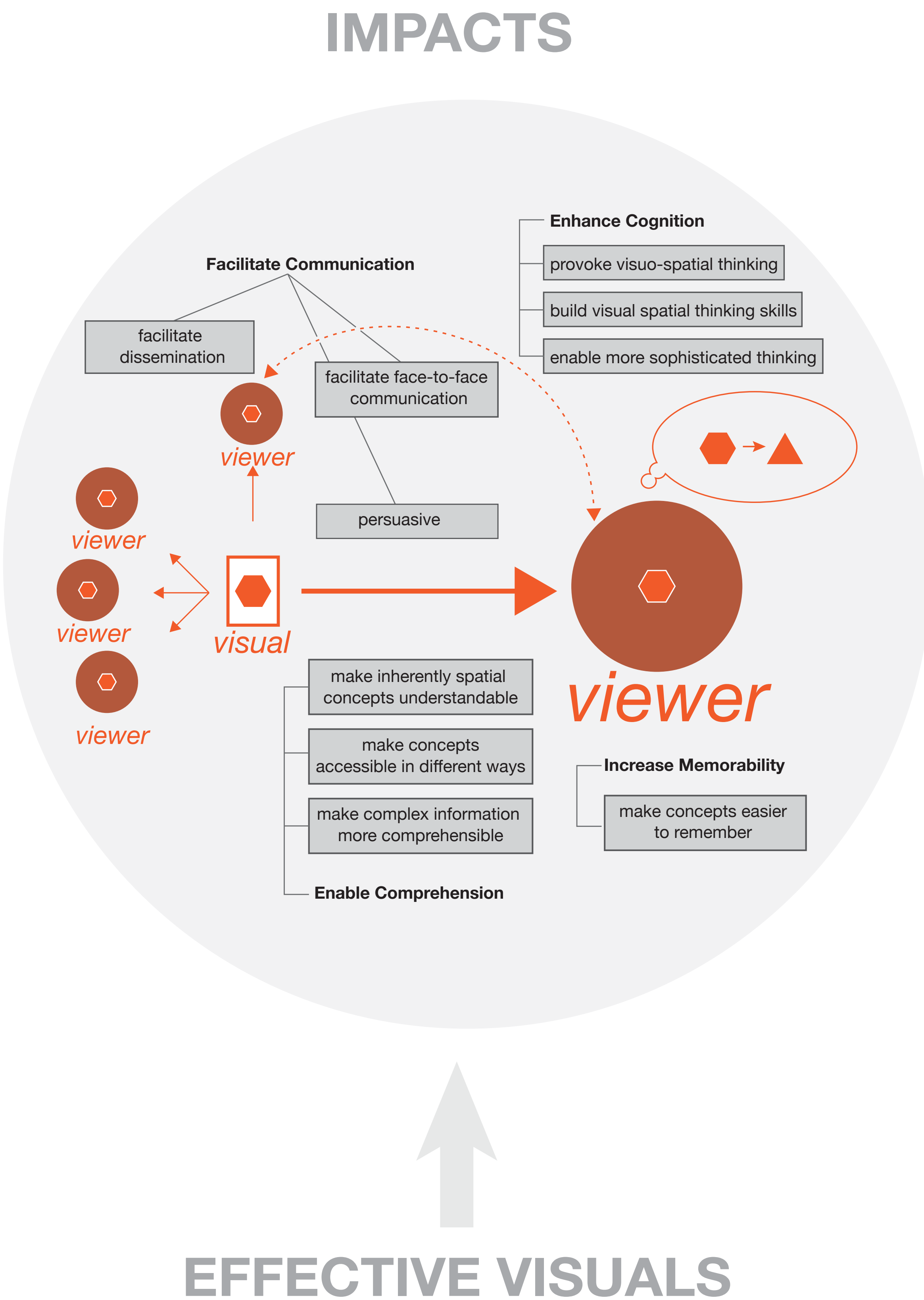


Figure 32a Desired impacts of science visuals derived from the *Visuals in Science* literature

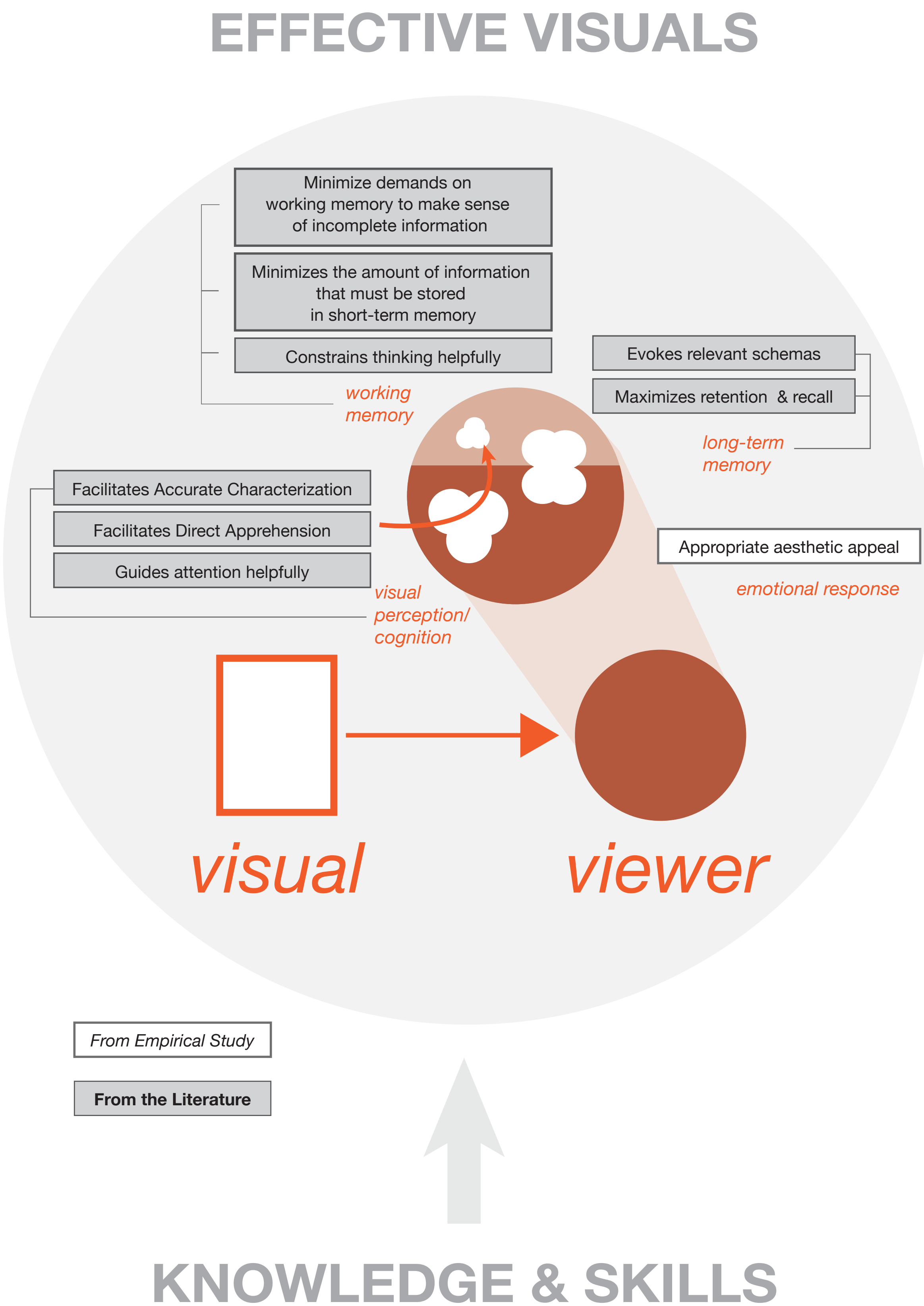


Figure 32b Attributes of effective visuals derived from the Empirical Study and the Effective Visuals literature

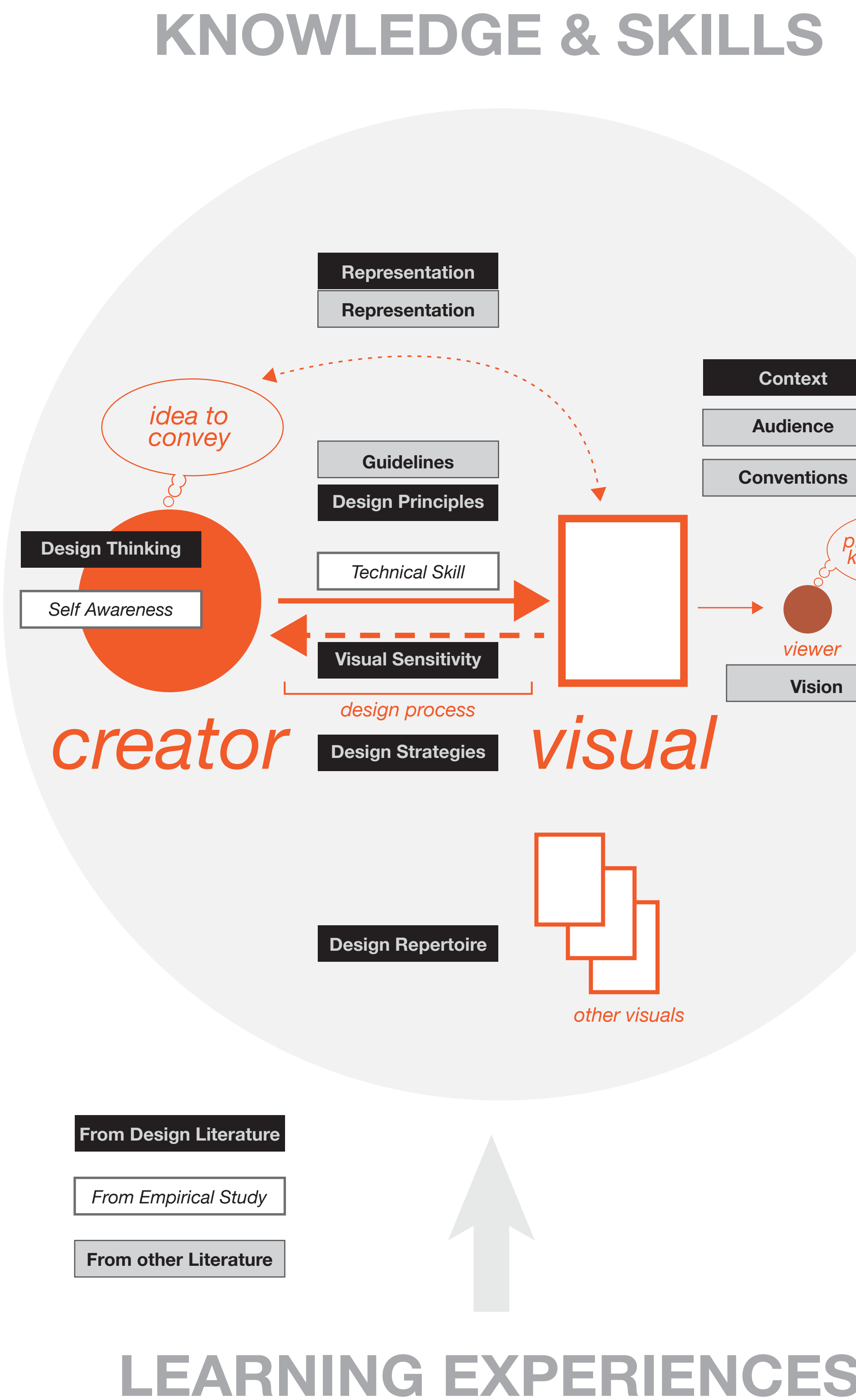


Figure 32c Skills and knowledge for creating effective visuals

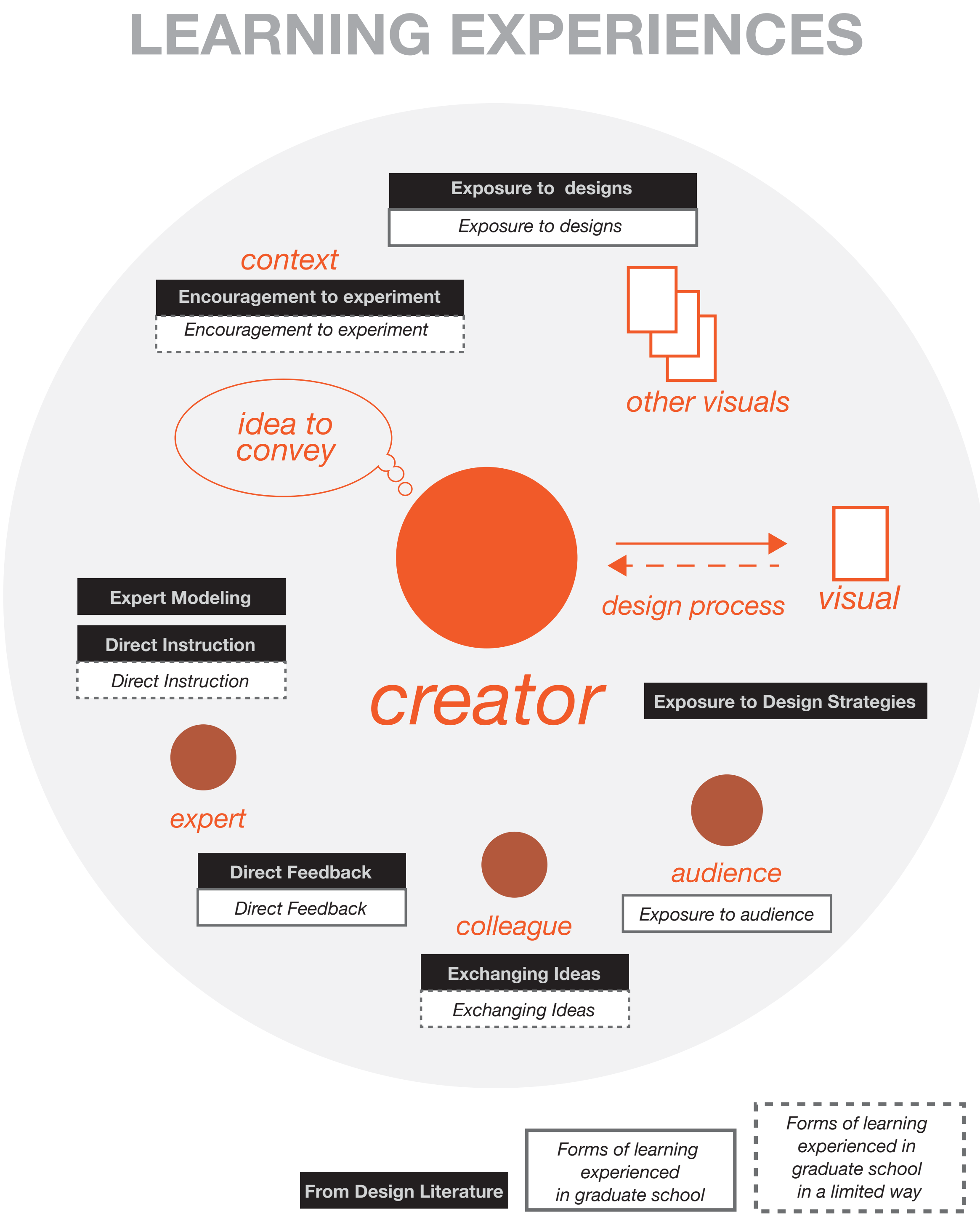


Figure 32d Learning experiences that foster the skills and knowledge for creating effective visuals

A tour of the framework

I will walk through the framework and reflect on what it tells us about competence in visual communication for scientists.

The *Impacts* circle contains 9 themes derived from the *Science Visuals* literature. These themes fall into 4 categories. Three of these categories: *enable comprehension*, *enhance cognition*, and *improve memorability* relate to what happens in the viewer's mind. The fourth category: *facilitate communication*, relates to what happens between and amongst viewers. If we step back and consider the scientific endeavor as a whole, we can see that these four impacts of science visuals are aligned with the fundamental nature of the practice of science as a means of generating new knowledge about the physical world through a massively distributed effort that consists of individuals acquiring existing knowledge (comprehending and remembering known facts and concepts), using this knowledge along with new evidence to generate additional knowledge (acts of cognition), and sharing that knowledge with others (communication).

The *Effective Visuals* circle contains 9 themes derived from the *Effective Visuals* literature. These themes fall into four categories—one that relates to aesthetic response (visuals are most effective if they provoke a context-appropriate aesthetic response) and three that relate to three components of processing visual information: visual perception (visuals are most effective if they maximize their reliance on visual perception); long-term memory (visuals are most effective if they optimize their use of information stored in long-term memory); and working memory (visuals are most effective if they minimize load on working memory). These themes reflect an underlying premise that effective visuals are visuals that use cognitive resources efficiently, with the caveat that minimizing conscious processing may limit learning since this form of processing is important for building new schemas. The aesthetic component of visual processing supports visual processing indirectly by directing attention and influencing motivation.

The arrow between the *Effective Visuals* circle and the *Impacts* circle represents the idea that a visual with the qualities identified in the *Effective Visuals* themes will produce the impacts identified in the *Impacts* themes.

The *Knowledge & Skills* circle contains thirteen forms of skill and knowledge derived from the *Design Expertise & Education* literature, the *Effective Visuals* literature, and the empirical study. In the diagram, they are arranged to show how they relate to aspects of the conception, creation and interpretation of visuals (e.g. the design process, the context in which the visual will be seen, and the relationship between the visual and the idea it represents). These 13 forms of knowledge and skill represent different *types* of knowledge and skill that range from the meta-level (self awareness), to the pragmatic (software skills), and from skills built on experience (visual sensitivity) to knowledge acquired through reading or direct instruction (knowledge about vision). Two consequential realities are reflected in this set of skills and knowledge as presented in the diagram; one is that competence in visual communication is profoundly multi-faceted; the other is that there are different perceptions of what these skills and knowledge are, which may reflect different approaches to creating visuals or may reflect the value of combining the wisdom of different perspectives.

The arrow between the *Knowledge & Skills* circle and the *Effective Visuals* circle represents the idea that an individual with the 13 forms of knowledge and skill is an individual who is capable of producing visuals with the qualities identified in the *Effective Visuals* themes. In the case of the knowledge and skills identified from the *Effective Visuals* literature, this link is often explicit – for example, the need to know about how a visual represents an idea is based upon research that shows that representation choices affect how visuals are perceived. In the case of the knowledge and skill identified from the *Design and Design Education* literature and from the empirical study, this link is either obvious (it is obvious that one needs to be familiar with the necessary software for creating a visual), or it is based not upon experimental evidence, but upon the wisdom of expert designers and the observations of researchers who study expert designers to understand how they differ from those with less developed design skills.

The *Learning Experiences* circle contains eight forms of pedagogy for learning to create effective visuals. They are associated with six elements present in the diagram – expert designers, peer designers, audience members, other visuals, the experience of the design process and the context in which the learning takes place. As the diagram indicates, with the exception of *exposure to audience*, all were identified in the *Design Expertise and Education* literature and six are present in the experience of graduate-level science students, although three are present in a limited way only. Two forms of learning; *exposure to design strategies* and *expert modeling* were not reported as present in the graduate school experience of the students who were interviewed, although those students who took the course did experience exposure to design strategies and six made comments suggesting that they appreciated and benefitted from this aspect of the course.

The arrow between the *Learning Experiences* circle and the *Knowledge & Skills* circle represents the idea that an individual who experiences those eight forms of pedagogy will develop the 13 forms of knowledge and skill for producing effective visuals. The *Design & Design Education* literature does talk about how those forms of pedagogy facilitate learning, although the connection between learning and skills or knowledge is not always made explicit and there probably is no 1:1 correspondence (e.g. visual sensitivity may be acquired through a combination of strategies including direct feedback, exposure to existing visuals and direct instruction). It is potentially problematic that there are no learning strategies explicitly geared toward the skills and knowledge that come from the empirical study and psychology literature, although intuitively, these may be acquired through a combination of direct instruction (e.g. to learn about vision and guidelines), and exposure (to learn about the audience and about visual conventions).

This ends the tour of the conceptual framework. Chapter 11 will discuss the limitations of the framework, how this framework (and this dissertation in general) contribute to knowledge generally, and the implications of this framework for practice and further research.

CHAPTER 11: CONTRIBUTIONS, IMPLICATIONS AND DISCUSSION

There were two main motivations for this dissertation. The first was the awareness that despite the acknowledged importance of visuals in science communication, little or no attention has been paid to the question of how scientists develop skills in visual communication. The second was the awareness that existing knowledge, if analyzed and organized with this topic in mind, could provide significant insight.

The work of this dissertation was structured around the four-part conceptualization of competence in visual communication shown in Figure 33.

Figure 33: 4-part conceptualization of competence in visual communication

This conceptualization characterizes competence in visual communication as knowledge and skills acquired through various learning experiences, which are used to produce effective visuals—visuals that have the desired effects, or impacts. The four research questions posed by this dissertation are aligned with this conceptualization:

1. What are the desired impacts of science visuals?
2. What are the characteristics of an effective visual – a visual that will have the desired impacts?
3. What skills and knowledge enable an individual to produce an effective visual?
4. What forms of learning experience develop the skills and knowledge that constitute competence in visual communication?
   a. How are graduate science students learning to create visuals?
   b. Is their education giving them the skills they need?
   c. Is instruction in visual communication valuable to science students?
   d. How do science students respond to formal instruction using design pedagogy strategies?

Two research strategies were used to address these question: two integrative literature reviews and an empirical study consisting of interviews with graduate-level science students and analysis of documents produced by science students enrolled in a course on creating science graphics. The themes identified in the data from these sources are described in chapters 5-9 and presented as a conceptual framework in chapter 10.

In this chapter, I will describe the contributions of this research, the limitations of this research, and the implications for practice and further research.

CONTRIBUTIONS OF THIS RESEARCH

The contributions of this research align with the four forms of scholarship identified by Ernest Boyer in *Scholarship Reconsidered: The Priorities of the Professoriate*: the scholarship of discovery, the scholarship of integration, the scholarship of application, and the scholarship of teaching.

> Surely, scholarship means engaging in original research. But the work of the scholar also means stepping back from one's investigation, looking for connections, building bridges between theory and practice, and communicating one's knowledge effectively to students. Specifically, we conclude that the work of the profesoriate might be thought of as having four separate, yet overlapping, functions. These are: the scholarship of discovery; the scholarship of integration; the scholarship of application; and the scholarship of teaching. — Ernest Boyer (1990, p. 16)

The scholarship of discovery

The contributions of the original research (the empirical study consisting of the interviews with science students and the observations of their responses to the course on science graphics) include a more complete picture of how graduate school prepares scientists for this one aspect of professional practice; a glimpse into the feasibility of using the pedagogical strategies of design in a science context; and perspectives on the four core research questions that complement those found in the literature.

The scholarship of integration

While the original research representing the *scholarship of discovery* was an important component of this dissertation, the core work—the integrative literature reviews and creation of the conceptual framework--represent the *scholarship of integration.*

Identification of key literature

This work began with the compilation of over 800 documents relating to science visuals—a collection with no easily discernable structure beyond the three major clusters (*Effective Visuals*, *Visuals in Science* and *Design Expertise & Education).* This collection was expanded to 1000+ documents and then whittled down to a core set through the process of defining and applying the inclusion/exclusion criteria for the integrative literature review. These final lists—appendices 1, 2 and 3 are one of the contributions of this work—92 core publications relating to the impacts of visuals in science, 125 core publications relating to what makes visuals effective, and 22 publications relating to the skills & knowledge of visual communication and the pedagogical strategies for fostering those skills and knowledge.

Intellectual access to new territory

Another contribution of this integrative work is the intellectual access the conceptual framework provides to territory not well explored in the academic literature. It does this by delineating the scope, boundaries, and internal structure of the topic area and then acting as a guide to an otherwise dispersed and hidden body of literature (hidden in the sense that it is not overtly presented as being about this topic—a search on "competence in visual communication for scientists" will not retrieve this literature).

A framework to build upon

In addition to identifying key literature and providing intellectual access to the territory defined by that literature, this work acts as a framework for accommodating additional literature. It does so by providing a model for how different ideas and perspectives relate to this topic. When a new publication is identified as being potentially relevant, it can be compared to the themes in the conceptual framework to determine where it fits relative to existing literature.

A challenge to intuitive understanding

Yet another contribution of this work is to challenge or expand upon our intuitive or narrowly-focused understanding of competence in visual communication. The conceptual framework presents *competence in visual communication* as a complex, multi-faceted phenomenon. The interview comments suggest that this complexity is not always intuitively appreciated—while participants made insightful comments about the skill and knowledge required to create effective visuals, none described the rich array presented in the conceptual framework. The value of recognizing this complexity is that it enables an appropriately multi-faced approach to fostering competence in visual communication.

Awareness of knowledge & gaps in knowledge

A further contribution of this work is to help us recognize both the extent to which existing knowledge can be leveraged toward optimally preparing students for scientific practice, and the specific ways in which existing knowledge is incomplete. It therefore enables more informed actions with a better appreciation of the potential for yet-to-be discovered knowledge to provide additional insight.

Tool for cross-disciplinary awareness

A final contribution of this work (as a form of integrative scholarship) comes from its juxtaposition of perspectives from multiple disciplines. This serves several purposes. One is to enrich understanding. Bringing these perspectives together reveals the multi-dimensional nature of creating effective visuals; it is simultaneously about design *and* about visual perception *and* about communication *and* about the nature of science. Another purpose is to help bridge divides between siloed disciplines by introducing those within a given field to aspects of the topic that are not typically addressed in the literature of that field.

The scholarship of application

> The first two kinds of scholarship—discovery and integration of knowledge—reflect the investigative and synthesizing traditions of academic life. The third element, the application of knowledge, moves toward engagement as the scholar asks, 'How can knowledge be responsibly applied to consequential problems? How can it be helpful to individuals as well as institutions? —Ernest Boyer (1990, p. 21)

Boyer's first two forms of scholarship—discovery and integration—refer to research activities. This third form of scholarship refers to practice. The work of this dissertation is not itself a form of practice, but it has a practice-orientation—the findings are intended to be directly applied to the consequential problem of producing scientists who can skillfully document and communicate their knowledge.

The scholarship of teaching

> Finally, we come to the scholarship of teaching. The work of the professor becomes consequential only as it is understood by others" (Boyer, 1990, p. 23). "Pedagogical procedures must be carefully planned, continuously examined, and relate directly to the subject taught —Ernest Boyer (1990, pp. 23-24)

Boyer's fourth and final form of scholarship is the scholarship of teaching. The work of this dissertation is not itself a form of teaching, but it directly informs teaching activities. In addition to identifying pedagogical strategies and learning outcomes, it provides the motivation and justification for directing attention to this area. It does so by presenting *competence in visual communication* as complex and multi-faceted—something that is difficult to acquire without guidance--and by providing evidence that this form of guidance may be lacking in the experience of graduate-level science students.

LIMITATIONS OF THIS RESEARCH

Here I describe limitations of this research. These include the absence of contributions by disciplines that could potentially provide valuable insights, but have not addressed this area; the absence of concepts that are not present in the bodies of literature examined, but have been addressed elsewhere; and by a focus on competence in visual communication in the present that does not explicitly account for changes resulting from new technologies.

Missing voices

While the conceptual framework incorporates ideas presented by a wide range of disciplines, there are some potentially important but peripheral ideas that have not been incorporated and there are disciplines which seem under-represented. The framework will be stronger when these missing elements are included. I describe these elements in more detail below. Another limitation of this framework is that it is somewhat static; it focuses on skills and knowledge relevant for current contexts and technologies. Below I also talk about how *competence in visual communication* may change in the future.

Missing voices—communication

One seemingly under-represented discipline that would presumably have a great deal to say about the desired impact of visuals is communication. The fact that the literature reviewed included such a small number of publications from this discipline is not from lack of effort to identify them—I actively searched the literature in this area, but encountered two obstacles; a (seemingly) overwhelming emphasis on verbal over visual communication, which means that references to visual communication are few and far between, and, amongst those few references to visual communication, an emphasis on photographic imagery, often in the context of mass media communication or advertising. This emphasis on forms of visual communication that are relatively far removed from science communication meant that most of what I found did not make the cut when I winnowed down my references to the most central for the integrative literature review. Yet it is worth mentioning that although they were excluded, there is some intriguing potential for these ideas to inform science communication. For example, in a chapter on Visual Literacy Theory by Paul Messaris and Sandra Moriarty (2005) the focus is on photographic imagery in mass communication and advertising described, yet it addresses many of the attributes of visuals that are important in science communication: spatial thinking, the ways in which visuals evoke analogical thinking, and the role of visuals in persuasion despite the fact that the.

Missing voices—scientists

The voices of scientists themselves are also somewhat minimally represented in the reviewed literature, though they *are* included via the sociologists, philosophers, historians and psychologists who study them as well as in their own writings. One question in regards to bringing in the perspective of scientists is whether some of the desired outcomes they identify may fail to be expressed in the literature because they are perceived as too mundane or pragmatic to be considered worthy of publication. This question is provoked by an observation that some of the ideas expressed by the interviewees are of a less lofty nature than those expressed in the literature. For example, one interviewee, when asked about the audience for his visuals, first mentioned journal editors—implying an orientation toward getting published rather than expressing the message clearly. Getting an article accepted for publication or receiving a grant are certainly desirable outcomes from the perspective of individual scientists and this might have implications for how an *effective* visual is defined. The considerations for creating a visual that is effective for a peer reader may be somewhat different than the considerations for creating a visual that is effective in the context of persuading a reviewer who is making comparative judgments about competing manuscripts.

Missing voices—designers

The voices of designers are well represented in the discussion on forms of learning and the discussion of the skills and knowledge of design, but absent from the discussion of the characteristics of effective visuals. This seems like an important oversight. But again, this is not the result of a lack of diligence in looking for these contributions; I broadened my search to include non-academic works in order to incorporate books written by designers. The challenge however, is that while these books talk about the components of design such as typography and color, they do not typically identify characteristics of an effective design. Two examples that are specific to science visuals are

Felice Frankel & Angela DePace's beautiful book *Visual Strategies: a practical guide to graphics for scientists & engineers* (2012), and Mary Briscoe's *Preparing Scientific Illustrations; a guide to better posters, presentations and publications* (1996). Both contain numerous before and after examples demonstrating improvements made to existing science visuals, but neither describes the characteristics of an effective design in a more abstract or generalizable form. Yet it seems clear that designers clearly have an important contribution to make here.

Missing voices—non-designers on teaching strategies and skills/knowledge

While designers' voices are missing from the discussion of what makes visuals effective, the voices of *non*-designers are missing from the discussion of teaching strategies. As I mentioned in chapter 9, this reflects the fact that there are no well-established traditions of teaching visual communication in other disciplines. However, since the list of relevant skills and knowledge for creating effective visuals includes some items that were not identified in the design literature, it suggests that these are forms of skill and knowledge not traditionally taught in design programs. This is echoed in the following quotes about the nature of information design: "Information design addresses this need by blending typography, illustration, communication studies, ergonomics, psychology, sociology, linguistics, computer science, and a variety of other fields to create concise and unambiguous messages" (Visocky O'Grady & Visocky O'Grady, 2008, p. 6). Designer Terry Irwin says that "Information designers are very special people who must master all of the skills and talents of a designer; combine them with the rigor and problem-solving ability of a scientist or mathematician; and bring the curiosity, research skills and doggedness of a scholar to their work" (quoted in Hembree, 2008, p. 33).

Missing voices—education

Since this dissertation focuses on learning that happens during graduate education, I searched for literature on the nature of learning in graduate school, but with little success. The article referenced in the introduction by Nobel prize-winner physicist Carl Wieman is an exception. He describes the nature of graduate education and the mechanisms by which it helps transform students into competent professionals. One intriguing aspect of this description is the parallel with studio learning – in particular learning-by-doing with expert guidance. "People learn by creating their own understanding. But that does not mean they must or even can do it without assistance. Effective teaching facilitates that creation by getting students engaged in thinking deeply about the subject at an appropriate level and then monitoring that thinking and guiding it to be more expert-like" (Wieman, 2007, p. 12). It would be valuable to include the perspective of education experts to expand upon these observations.

Missing concepts in this analysis

In chapter 4, I listed the inclusion/exclusion criteria for determining which documents were included in the integrative literature reviews. The purpose of these criteria was to ensure that the reviews were focused on the most pertinent literature. However it also meant that potentially relevant literature was excluded. Some of these are described below.

Missing concepts—vision research

Each of the inclusion criteria for the integrative literature review specifies that the work under consideration refer to visuals, meaning visual presentations of information. This excludes the research on visual perception that looks at how we interpret visual elements in isolation. Such research clearly has implications for how we perceive elements in science visuals.

Missing concepts—affect and aesthetics

I referenced literature on the neurobiological role of emotion and aesthetic appeal in affecting visual perception in chapter 3 and include *theme B10: An effective visual has an appropriate aesthetic appeal* based on comments in the interviews. But there is more literature that did not meet the inclusion criteria, but could potentially provide relevant insight. An example from this literature is an article by Kevin Larson and Rosalind Picard, *The Aesthetics of Reading,* which presents evidence that high quality typography induces a positive mood in the viewer (Larson & Picard, 2005).

Competence in visual communication as a moving target

Another limitation of this framework is that it does not explicitly address the nature of competence in visual communication as a moving target. Both the science being represented and the tools for representing it are changing and the skills for creating visuals in the future may be different than those in the current list. For example, new software, faster processors and online publishing are making it easier to incorporate animation and interaction while new hardware such as virtual reality systems and massive screens present new contexts in which visuals may be viewed. These new displays challenge us to understand and leverage aspects of visual cognition that are not part of traditional graphic design and the literature reviewed here primarily focuses on static visuals that fit on a small page or screen.

IMPLICATIONS FOR PRACTICE

Each of the 4 elements of the conceptual framework plays a role that motivates and informs action to improve competence in visual communication. The first, *Impacts* clarifies how developing this form of competence supports the ultimate goal of furthering science (along with the immediate goal of furthering one's own research). The second, *Effective Visuals*, lays out why not all visuals are equal and creates a clearer picture of how to achieve the desired impacts. The third, *Skills & Knowledge*, shows that the ability to create effective visuals comprises much more than knowledge of software and conventions, and implies that this ability is something that can be systematically cultivated. The fourth, *Learning Experiences*, acts a guide for practice and reveals a discrepancy between the array of experiences that cultivate *competence in visual communication* and the experiences provided to graduate-level science students.

What would a curriculum look like?

Based on the work of this dissertation, I have put together a curriculum model that incorporates the recommendations implicit in the conceptual framework:

Meta-awareness

By *meta-awareness*, I mean developing an explicit understanding of the nature of visual communication broadly to create a context and purpose for attending to the finer details. Curriculum subjects would include:

- What is the role of visuals in science (communication, comprehension, cognition)
- What is the nature of design (a process that requires strategies to stimulate ideas)
- What is the nature of vision (visual perception, working memory and long-term memory)

Vision

As noted previously some consider an understanding of vision to be a valuable basis for making design decisions (MacEachren, 2004; Ware, 2000) although it is not a traditional part of a visual communication design education. This form of knowledge may be particularly relevant for scientists as people who are skilled at understanding the world via scientific concepts. Curriculum subjects would include:

- The nature of various aspects of vision such as color perception including the functional implications of why vision is the way it is
- The nature of foveal versus peripheral vision
- Types of visual input that are processed in independent neural pathways
- Complementariness of verbal and visual pathways
- Pre-attentive processing & gestalt processing
- Role of attention in perception (e.g. change blindness)
- The limitations of working memory and strategies for minimizing cognitive load (chunking, reliance on perception)

- The nature of long-term memory & schemas (leveraging knowledge-of conventions, compensating for missing knowledge)
- The impact of affect and aesthetics on interest, attention and judgment of credibility

Design rules and principles

Here the rules from cognitive psychologists and the principles from design (many of which originated in the fine arts) are combined since they are all guidelines for design decisions. Some of these principles/rules were presented in the summer course and references made to this aspect of the course in the interviews and course evaluations were positive. Learning these guidelines involves both being presented with them in verbal/visual form and having the experience of using them to them to make design decisions. They include the following:

- Uses of color & text
- Guidelines for combining words & images
- Principles for mapping perceptual attributes to conceptual attributes
- Guidelines for choosing when to use visuals (versus text)
- Using contrast & visual hierarchy to direct attention
- Using value for legibility & contrast
- Using color harmonies – to avoid discordance
- Create unity and variety for a coherent, yet interesting presentation
- Using visual layering to reduce the sense of overload

Making visuals responsive to the viewer/viewing context

Making visuals responsive to the viewer and viewing context refers to customizing a visual to a given audience and format (journal article, conference presentation, poster, lab meeting). Learning to do this is not about learning new concepts, but learning to think about how a visual can be redesigned for different contexts and also learning how people perceive visuals differently by hearing their feedback. It is also about looking closely at the nature of visual conventions—considering how they help or hinder the viewer (who may not be familiar with them) and also confronting one's own assumptions about just what those conventions are by talking with others and exploring the range of variation present in published visuals.

Turning an idea into a visual

Turning an idea into a visual refers to the process-oriented nature of generating a design. This was another aspect of the course that several participants responded to positively. Curriculum goals related to this would include the following:

- Learning how to benefit by creating parallel designs
- Learning how to benefit from giving and receiving critique
- Learning how to approach the creation of a visual as a design problem
- Learning technical skills—finding optimal tools and developing a basic array of skills

Additional skill building

The various curriculum elements described above all include skill-building components, but two important skills that aren't reflected explicitly are developing visual sensitivity and a personal repertoire of effective visualization strategies by analyzing existing visuals and being exposed to an expert's analysis.

Structures for presenting this curriculum

The summer course described in chapter 4 is one model for introducing learning experiences that will help graduate students develop competence in visual communication: a specialized setting in which students are exposed to design processes and concepts with the guidance of an expert designer. One concern about such a course, which was expressed by two of the participants, is the difficulty in justifying the time it takes away from research work, although this is perhaps countered by the point made by several others that learning on their own was also not a good use of time. The idea might be to identify a combination of strategies for embedding these learning experiences into the graduate school experience in ways that ease the burden of developing these skills while not adding an additional burden. Some strategies for achieving this are outlined below. Each incorporates one or more of the forms of learning from the conceptual model:

Workshops

Periodic workshops, such as the ones described by two interview participants in which a lab group devotes a meeting to visual communication would be one strategy for providing direct instruction (e.g. software tips, design principles, vision concepts). If led by an expert in visual communication, it could also be an opportunity for expert modeling and feedback. If it involved hands-on exercises, it could also be a way to introduce students to design strategies. Ideally the workshops would be coordinated to build upon each other and held frequently enough to reinforce previously introduced ideas.

Critique training (expert modeling, direct feedback)

In the course, students learned to give and receive critique through a combination of modeling by a professional designer who structured and led a critique session, and one-on-one peer critique sessions which the students prepared for by filling out a form which guided their feedback (e.g. they were asked to first describe what they saw in the visual, then paraphrase the message they received, then identify both what made the visual effective and what was problematic). This same structure could be used with lab groups by bringing in a professional designer to model the critique process and then provide a suggested structure for useful feedback.

Model visuals (repertoire)

During the interviews, 18 of the 22 participants said they learned to create visuals by seeing what others had done. This echoes the previously-quoted comment by Luc Desnoyers: "…it is our experience that students resort to learning by doing and imitating what they read and see, for better or for worse" (Larson & Picard, 2005). The downside of this learning strategy is that poor practices may be perpetuated. The upside of this learning strategy is that if more effective strategies are introduced, they may be perpetuated as well. If, for example, a designer is brought in to help a lab group produce a strikingly effective poster that is within the technical reach of most students, this poster could be displayed in the hallway where others in the building would have a chance to see and emulate it.

Software and conceptual tutorials

A limitation of the class model is that students will be at varying stages in their development of visual communication skills and therefore instruction that is useful for one student will be out of reach for another who is not ready and redundant for a third who has already learned the concepts. One way to address this challenge is to provide self-guided tutorials that students can access as needed. This would be a form of direct instruction and would be a particularly appropriate strategy for learning software but could introduce design principles as well.

Figure club

Several of the students interviewed made reference to participating in journal clubs – meetings with other scientists to review and critique recently published developments in the field. This model could be extended to the idea of a "figure club" in which scientists would gather to critique recent published visuals (or their own visuals). This might be particularly valuable if it drew scientists from many disciplines since one characteristic of the class that students particularly appreciated was the opportunity to hear critique from fellow scientists outside of their own discipline—an opportunity that is not generally provided by the graduate school experience.

Help desk

One interview participant mentioned that she had received valuable instruction in making her visuals more effective from a statistics support service. This model could be extended to a design support service (such as the Design Help desk provided for students at the University of Washington with support from the Design Division in the School of Art). This would be an opportunity for students to receive feedback and modeling by an expert designer at the time the need arises

FUTURE RESEARCH

This dissertation can serve as a foundation for a line of research that looks explicitly at how scientists develop competence in visual communication. Ideally, this research would be conducted by teams composed of representatives from a range of disciplines including psychology, sociology, communication, information science, design and science. This research could take many forms including the following:

Experimental interventions

The course described in chapter 4 represents one strategy for incorporating some of the learning experiences listed in the conceptual framework into the graduate school experience. Other strategies are described in the *implications for practice* section above. A useful line of research would involve testing the efficacy of these strategies in terms of student and faculty perceptions of their impact relative to the level of resources required to implement them, and in terms of evidence that students are acquiring the forms of skill and knowledge listed in the conceptual framework.

Case studies of visuals & visualizers

Several of the articles reviewed used a case study methodology in which the author examined the impacts of a single visual or group of visuals. A case study approach could also be used to further explore the components of the conceptual framework. For example, a researcher might follow a graduate student producing a visual for publication using a case study approach to document all four dimensions of the framework including how the visual impacts the viewers (e.g. this might include responses to the visual in a lab group presentation), what qualities influence its effectiveness (how well it aligns with the qualities identified here), what skills the creator brought to bear to produce this particular visual (was it modeled after other visuals? were there software-related barriers? did the student use a design process they had learned previously?), and what learning experiences/learning environment helped the creator develop those skills (had they seen these skills modeled by others, had they been given guidance by an advisor or peer?).

The students interviewed for this dissertation described varied level of support for developing visual communication skills. Another case study approach would involve looking deeply at the impacts on students of an advisor who places particular emphasis on the visual communication skills of his or her students. This might involve interviews with the advisor, his or her students and students in nearby labs who are aware of the visuals this lab is producing (e.g. as a result of seeing their posters lining the hallways).

Interviews about the impact of tools/technologies

As described in chapter 8, there was little mention in the literature of the role of software in facilitating or impeding the creation of visuals, although it was a significant part of the student experience. It would be valuable to conduct research in this area to understand ways in which software acts both as a facilitator and a barrier. This could involve interviews with students and/or experiments in which software skills were introduced using tutorials or other teaching strategies.

Observation of learning experiences

One limitation of this work is that it relies on students' self-reports of their learning experiences. While it might be difficult to observe moments of learning as they happen, additional information could be gleaned from a more situated, longitudinal study which involved visiting the office and laboratory settings where students work and conducting interviews with lab members about events related to creating or learning to create visuals that happened in the previous weeks.

Interviews with other scientists

Interviews with additional scientists would complement the student perspective provided presented in this dissertation. In particular, it would be helpful to hear from graduate advisors who have seen many students develop their visual communication skills over the course of their graduate education. I mentioned previously that those who review papers for publication in journals, for presentation at conferences or for grant applications are a particularly critical audience so it would be useful to hear their perspective on how the quality of visuals affects their ability to process the information and the judgments they make.

Summary

The common goal of these various forms of research is to further enrich the understanding of competence in visual communication that is captured in the conceptual framework and then to modify and strengthen the framework itself as the basis for future research.

CONCLUSIONS

The historical evidence (e.g. Gross et al., 2002), as well as the observations of philosophers (e.g. Bruno Latour, 1986), sociologists (e.g. Kozma et al., 2000) and scientists themselves confirm that visuals play an important role in communicating and conducting science. Yet scientists face the complex task of communicating visually with relatively little formal preparation. The goal of this dissertation has been to lay out an articulation and conceptualization of *competence in visual communication* that can be used as a basis for developing strategies to enrich the graduate school experience in ways that better enable graduating scientists to excel in this aspect of professional practice.

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APPENDIX 4: INTERVIEW SCRIPT

I'm going to ask you some questions about creating science visuals. First I'll explain what I mean by that. I'm referring to things like drawings, illustrations, graphs, diagrams or images – anything where you're putting information into something visual or graphical as opposed to written. The context doesn't matter – it could be something you write in your notes in a lab or something you put in a publication or presentation, or something you draw on the back of a napkin to explain to a friend.

Interview questions:

- Do you create science visuals in your research/education? (follow-up questions would include: Has that been a course requirement or a request made by your advisor? Who is the audience for the visuals you've created? What contexts do you make visuals for…for lab work, your own notes, for presentation or publication?...
- How have you learned to make visuals? (follow-up questions would include: Have you taken courses in visual design? Have you been taught or taught yourself graphics applications? Have you learned principles of design or principle of good presentations?)
- What makes a science visual successful or unsuccessful?
- What skills/knowledge do you feel it takes to make successful science visuals?
- Do you feel that your education has helped you develop the skills you need for creating visuals in your future work as a scientist? Is this something you've thought about before/since we last spoke?

On a scale of 1-5, how important are visuals in learning and teaching science?

Not important extremely important

1 2 3 4 5

On a scale of 1-5, how important is it to be able to create one's own visuals?

Not important extremely important

1 2 3 4 5

On a scale of 1-5, how valuable is to teach students to create visuals (rather than letting them figure it out on their own)?

Not valuable extremely valuable

1 2 3 4 5

What is your major?