Visual Intelligence:
Bridging the Gap from Visual Literacy to Visual Reasoning

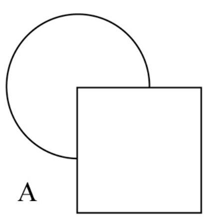
Jayme Jacobson and Greg Turner-Rahman

Introduction

The concept that visual thinking is a powerful form of analytical reasoning bridging virtually all of human activity is not a new idea. For decades, beginning in the 1950s, psychologist Rudolf Arnheim argued persuasively that educators had overlooked a gold mine of human intelligence by failing to recognize and train one of the most powerful aspects of human cognition: visual thinking.[1] During the same period, Gyorges Kepes and his colleagues at MIT's Center for Advanced Visual Studies strove to understand the interconnectedness of art and science by evaluating similar modes of problem solving across domains.[2] More recently, arguments by Ferguson, Miller, Gooding, and many others[3] have essentially arrived at the same conclusion, that visual-spatial reasoning is an integral and fundamental part of complex problem solving in multiple domains. Given the cogency of these arguments, it might seem surprising that there is any hesitation in pursuing the rigorous training of visual-spatial reasoning through praxis, but the fact remains that currently there is little emphasis placed on honing the visual-spatial skills that would enhance critical and integrative thinking across disciplines. In this paper we enumerate the reasons for this resistance, correct misunderstandings about the limitations of visual-spatial reasoning, and consider what aspects of our current technologies are propelling us to reconsider visual-spatial competencies.

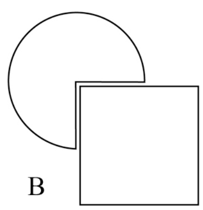
Can reasoning be visual?

First, it must be acknowledged that firmly cemented in the minds of many people is the notion that reasoning—or hard logic—must be expressed in a verbal or numerical format. Ironically, a large part of the blame for this misconception can be placed on the efficiency of the visual system itself. Even after more than a century of empirical evidence that perception is an active, ongoing process of logical calculations, there is still resistance to the idea that perception is cognition. Nothing is passive about seeing; the visual system uses a large percentage of the brain to perform a constant stream of deductive reasoning. Without this reasoning, we would not be able to "see" the three-dimensional world from the limited two-dimensional input nature has given the brain to work with. As an example, consider the two geometric shapes in Figure A.



A

To "see" these two shapes and comprehend their spatial relationship, the visual system has to perform a number of calculations. The conclusion that it would normally draw is that the square is in front of the circle. The visual syllogism for this operation would be: opaque shapes occlude shapes that are behind them *(major premise);* a square is occluding a circle *(minor premise);* it follows that the square is in front of the circle *(conclusion).* Just as with verbal logic, if either of the premises is false, the conclusion will be flawed. Figure B illustrates one way that the minor premise could be flawed: the square was not occluding a circle but rather abutting another kind of shape. Visual illusions are interesting to perceptual researchers not because they highlight flawed reasoning but because the offer clues about the rules that the visual system relies on. These rules are not always obvious. We might expect this example to be dependent on conventional geometric shapes but that is not the case.



B

Although a great deal of visual reasoning takes place with no apparent effort on the part of the viewer, more effortful forms of visual reasoning are required in variety of problem-solving situations. Gooding[4] proposed that reasoning in many domains relies on a common multi-step process of visual inference when novel phenomena are being explored. As an example of visual inference, Gooding used Whittington's paleobiological work reconstructing extinct organisms with no known present-day counterparts. To accomplish this reconstruction, Whittington produced 2D drawings of life forms that he had painstakingly pieced together from the fossil fragments of multiple creatures, solidified at varying angles in the rock bed. From these drawings he inferred 3D models, which were then verified against the fossil evidence. It is during the process of moving back and forth between 2D, 3D, and even 4D movement models that Gooding insists a form of visual dialectical reasoning is occurring. Moreover, Gooding asserts that mental imagery is insufficient for complex theoretical problem solving. In his analysis of Faraday's work on electromagnetism, Gooding proposed that the scientist's drawings were "tools for thinking," tools that made it possible for Faraday to move back and forth between concrete models of force and space to theoretical visualizations; and that this kind of visual reasoning via active manipulation was more potent than mere mental visualization, which lacks the "integrative power" provided by the interplay between image manipulation and inference. [5]

B

Miller suggested that a major reason for visual-spatial thinking in domains like physics, where many problems have no corresponding real-world visual references, is that in order to explore a theory, a physicist must be able to grasp the lay of the land, to narrow the lines of inquiry, to form, as Heisenberg put it, "an impression of how things are connected." Without visual models constructed from the mathematics of a theory, it is difficult to "make sense," to determine hypotheses for experimental data.[6]

These examples of visual reasoning in the sciences are not to suggest that visual reasoning is not occurring in fields more traditionally associated with visual media but rather to highlight that the reasoning taking place across diverse fields share common strategies and goals. Roger Malina observed that there were more "shared traits of personality and cognitive strategy" than differences between the artists, scientists and engineers he has worked with in his role as editor of the journal, *Leonardo*.[7]

An example of visual reasoning in the arts can be seen every time artists attempt to represent real-world phenomena. To produce, say, a drawing, the artist must determine what essential features will communicate the objects or scenes. For while it is possible to create what is termed a "photorealistic" rendering, there is, in fact, always a process of weighing what is important and what is not, of selecting essential elements and editing out inessential, ambiguous, or confusing elements. VanLeeuwen[8] noted a dialectical process of imagining, sketching, and evaluation even in the production of purely abstract work. Sketching and evaluation are necessary steps, he claims, because while synthesis is possible using only imagery, analysis is difficult; the artist cannot realize the transformations required to reach a satisfactory final product without sketching and evaluating—in other words, without external cognitive aids.

In the case of architecture, the designer must continually work between mental representation, sketch, and physical model in a re-iterative manner, sometimes referred to as 'seeing-moving-seeing' wherein the designer externalizes mental representations through the act of drawing[9] and, because of ambiguities in the translation, can reevaluate the image. From this the emergence of shape propels a continual cycle of the redevelopment of an idea. For architects and designers, the act of ideating through a sketch is not a solitary act of faithfully representing a mental image but a dialectic process. Rudolf Arnheim explains that, "it does not take place between the drawing and the mental image but rather between the goal image and its realization, at both levels – the mental percept and the optical percept, the imagination and the sketch."[10] For the architect, the complexity of considerations – overall visceral qualities of a design to intricate detailing and engineering – requires learned experience supplemented sometimes by model making or computer-aided simulation [11] which further expands the ability to construct from abstractions of memory. The process of working between "perception, physical experience, and conceptual idealization" is identical to scientific problem solving.[12] This recursive cycle is tantamount to visual reasoning thus the lived experience and the act of producing something, drawn from and fed back into the visual memory, are integral.

All of these reasoning processes used by artists, scientists, engineers, architects, and designers share a common goal: understanding through the analysis of essential structure.

Information sifting and essential structure: a means of understanding

One anecdotal story that helps to illustrate the challenges of determining essential structure comes from an undergraduate biology class in which the assignment was to draw and label the internal organs of a cat. The students were furnished with a cat cadaver as a model but they rebelled, demanding that the laboratory assistant provide them with some sort of diagram or schematic of the feline system to work from. It would seem that the cognitive demands of determining the essential components of a cat's internal system from real-life viscera were just too high. The act of translating messy, complex information into a schematized drawing illustrating the organs and their relationship to one another would be difficult for anyone not already familiar with mammalian organ systems; nothing in our present educational system would have prepared the biology students to delineate the critical components of the feline organ system through the process of drawing. No part of present or past systems have seriously considered the cognitive strategies involved in producing this kind of rendering directly from life; even in the late 1500s, when detailed anatomical and botanical illustrations were at their apex, the majority of illustrations were drawn from other illustrations, not directly from life.[13]

To make sense of any system, it is necessary to sift through extraneous information to determine which components are critical and how those critical components are related. Recognizing this kind of deep structure takes practice. Understanding deep structure requires repeated, hands-on practice no matter what the mode of reasoning is, be it verbal, mathematical, visual-spatial, kinesthetic, or a combination of modes. The tradition in education is to focus on the practice of verbal and mathematical skills. There is good reason for this; practice promotes understanding; doing catalyzes thinking. The neurologist, Frank R. Wilson has suggested that human neural structures coevolved with the hand's capacity to manipulate the surrounding environment.[14] Forms of external cognition like writing and calculating help to clarify thought and reveal inconsistencies in reasoning. Similarly, visual production can be used as a form of external cognition, but for two reasons we will consider next, it has been generally overlooked, if not outright rejected, as a means to reasoning.

Visual production as a vocational skill

Until recently, the process of visual production involved numerous individuals performing a variety of highly skilled functions that required expensive materials and elaborate machinery in order to realize a final product. For example, twenty years ago a typical piece of printed material would include the work an art director, copywriter, proofreader, layout artist, photographer and/or illustrator, typesetter, galley proofreader, paste-up artist, photostat maker, photoprint maker, cameraman/color separator, film stripper, plate maker, pressman, and finishers involved in trimming, folding, etc. This entire process can now, of course, be performed by anyone with a laptop and a color printer. All of those vocational skills have been collapsed such that one person can produce—with virtually no financial risk—full color visual communication. The same is obviously true for a variety of other forms of visual media such as film, animation, etc.

The exponential growth in visual software is quickly making it apparent that what is standing between most people and their ability to produce cogent visual communication is not skill or technical expertise but rather an underdeveloped capacity for reasoning in visual-spatial formats. Currently in education, much emphasis is being placed on decoding and interpreting visual information, to make viewers more literate and analytical about what they are seeing. What is not generally conceded is the poor quality of much visual communication, be it professional or amateur. Our argument in this paper is that it is not students' skills in comprehending visual messages that needs improvement, but rather their abilities to produce coherent visual messages. For instance, correctly interpreting graphs may be important—but more pressing is need for better graphs. Producing clear, organized visual communication requires visual reasoning, which requires hands-on manipulation; the problem is that in academia there remains an outdated bias that visual production is a vocational, not an intellectual process.

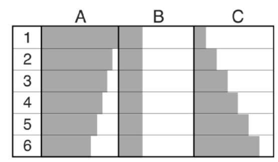
Images and the question of precision

The second impediment to promoting visual reasoning skills is that they have traditionally been viewed as simply a murky precursor to more to more abstract, precise verbal or numerical forms of synthesis. Kaufmann developed a problem-solving continuum in which the 'strong' methods of reasoning (linguistic propositional/numerical) are used for problems that are "programmed, familiar, structured, rehearsed, simple, and clear-cut," and the 'weak' forms (visual/spatial) are used for problems that are "non-programmed, novel, unstructured, ambiguous, and complex"—in other words, visual-spatial reasoning is resorted to when problems are difficult. Brain imaging studies reveal subjects rely on visualization in the early stages of complex problem solving, reserving verbalization for the summarizing phase.[15]

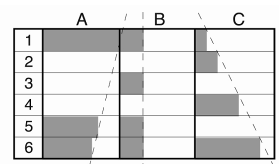
Transforming internal imagery is notoriously effortful which is why tools for externalizing cognition are so important. Modes of external cognition are not unconnected. In a simple but clear demonstration, Perini showed that tables are a form of external cognition bridging linear and spatial formats.[16] The following is and adaptation of Perini's argument. Precise information can be ordered in a linear format as seen in the figure below on the left but the cognitive load of interpreting the data is high. In contrast, spatial formats like a table can include all of the same numerical information but the alignment of information makes it easier to spot the trends especially if extraneous information, like decimal points, is trimmed. The table on the right shows how an extension of this idea by representing the same information in a purely visual format that uses area to denote quantity:

A1: 10.2334, B1: 3.1674, C1: 1.6201, A2: 9.5271, B2: 3.1753, C2: 3.0022, A3: 8.8432, B3: 3.1650, C3: 4.4203, A4: 8.1302, B4: 3.1830, C4: 5.8117, A5: 7.4413, B5: 3.1602, C5: 7.2236, A6: 6.7264, B6: 3.1736, C6: 8.6105

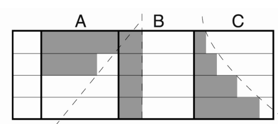
	A	B	C
1	10.2334	3.1674	1.6201
2	9.5271	3.1753	3.0022
3	8.8432	3.1650	4.4203
4	8.1302	3.1830	5.8117
5	7.4413	3.1602	7.2236
6	6.7264	3.1736	8.6105



	A	B	C
1	10.2334	3.1674	1.6201
2			3.0022
3		3.1650	
4			5.8117
5	7.4413	3.1602	
6		3.1736	8.6105



	A	B	C
	1: 10.2334	1: 3.1674	1: 1.6201
	5: 7.4413	3: 3.1650	2: 3.0022
		5: 3.1602	4: 5.8117
		6: 3.1736	6: 8.6105



It is through *alignment* that the relationship between the nodes of information is maintained. The example at right demonstrates that data can even be removed; as long as it remains aligned the trends can be correctly inferred. If, however, the alignment is removed in one dimension, it is more difficult to understand—to get a true picture—of the trends in the data. The general trend is still visible in that there is obviously an inverse correlation between variables A and C but, without mentally realigning the data, the picture is misleading.

What these tables illustrate is that visual spatial information is not inherently less precise than linear information but rather that precision must be maintained in more than one dimension. Precision is a concern when communicating all types of data. Artists and designers continue to explore ways to best impart succinct visual messages. New media technologies allow anyone to likewise explore in an open-ended manner thus it is imperative to learn to use visual production as a cognitive act to elicit efficacious communication or, in least, better understand the motivation of the communicator. A key aspect of this process is engaging in the dialectic between visual and mental representation through the manipulation of images until an optimal solution or essential structure is revealed.

Visual reasoning in the curriculum: cross domain problem-solving

At the University of Idaho, fine artists, printmakers, and graphic designers worked as information designers assisting Mark Klowden, an entomologist studying the Anopheles mosquito's sperm, in analyzing large amounts of data. Students used sketches and schematics to explore ways of representing the complexities of data in a manner that ultimately revealed new information about the size of sperm at stages of the Anopheles mosquito's maturation.

Similarly, students in Virtual Technology and Design worked with microbiologist Gustavo Arrizabalaga in a project to visualize the invasion of *toxoplasma gondii* into cells eventually producing cysts in the brain and muscles tissue. Students, who more often than not study the development of video games and special effects, underwent intensive instruction under Gustavo's tutelage. Teams of students then used sketches on whiteboards to ideate how they would represent the various processes. Moving from written materials and casual conversations with Arrizabalaga to the pre-visualization sketches and storyboards revealed interesting inconsistencies in both the written accounts in the research and in the veracity of the digital representation. When Arrizabalaga asked that models and animations be altered, the resulting reevaluation on the part of the students brought about further questions that he had to consider. The production of the final animation, which is perhaps better thought of as a metaphorical model for the processes of *gondii* invasion, became an excellent tool for exploring intricate and complex microbiological phenomena. The digital toolset augmented pen and paper to give both the artists and the scientist different ways of thinking visually.

Conclusion

The honing of visual reasoning through praxis has historically met with a number of roadblocks; misconceptions about the level of precision that can be commanded through modes of reasoning not traditionally associated with "hard" logic; biases against visual production as a either a set of specialized vocational skills or a form of non-analytical unstructured self-expression. Although visual reasoning has maintained a barely-acknowledged place in many domains beyond the visual arts it is only recently that technology has provided a means for the average person to produce visual media rather than passively consume it; to harness visual media as a form of external cognition. The problem is that intelligent visual-spatial ideation requires a form of dialectical reasoning that has been, for the most part, overlooked by contemporary academia. To neglect the integration of visual production as part of a problem-solving curricula is, at best, to put students to a risk of being weak communicators and, at worst, to deny them an important aspect of cognition.

Notes

[1] R. Arnheim, *Visual thinking,* Berkeley, CA: University of California Press, 1969

[2] G. Kepes, *Education of vision,* New York: George Brazillier, 1964

[3] E.S. Ferguson, *Engineering and the mind's eye*, MIT Press, 1994; A.I. Miller, *Insights of genius: Imagery and creativity in science and art,* Copernicus, 1996; A. I. Miller, *Imagery in scientific thought*, Birkhäuser, 1984; D. C. Gooding, 'From phenomenology to field theory: Faraday's visual reasoning', *Perspectives in Science,* 14, 2006, pp. 40-65

[4] D. C. Gooding, 'Seeing the forest for the trees: Visualization, cognition, and scientific inference', in M. Gorman, D. Gooding, R. Tweeney, and A. Kincannon (Eds.) *Scientific and technological thinking,* Lawrence Erlbaum, 2005, pp. 173-217.

[5] D. C. Gooding, 'From phenomenology to field theory: Faraday's visual reasoning', *Perspectives in Science,* 14, 2006, pp. 40-65.

[6] A.I. Miller, *Insights of genius: Imagery and creativity in science and art,* New York: Copernicus, 1996.

[7] R. Malina, 'Welcoming uncertainty: The strong case for coupling the contemporary arts to science and technology', in Jill Scott (Ed.) *Artists in labs: Processes of inquiry*, Springer-Verlag. 2006, p.16.

[8] C.Van Leeuwen, I. Verstinjen, & P. Hekkert, 'Common unconscious dynamics underlie common conscious effects: A case study in the iterative nature of perception and creation', in J. S. Jordan (ed.*), Modeling consciousness across the disciplines*, University Press of America, 1999, pp. 179–219.

[9] G. Goldschmidt, 'The Dialectics of Sketching', *Creativity Research Journal*, 4, pp. 123-124; D.A. Schon and G. Wiggins, 'Kinds of Seeing and their function in designing', *Design Studies*, 13, 1992, pp. 135-156.

[10] R. Arnheim, 'Sketching and the Psychology of Design', *Design Issues*, Vol. IX, Number 2, p. 17.

[11] R. Oxman and B. Steich, 'Digital Media and Design Didactics in Visual Cognition', *Education & Curricula – 07 The Ideal Digital Design Curriculum*, p. 190.

[12] R. Arnheim, 'Sketching and the Psychology of Design', p. 16.

[13] D. Topper, 'Towards an epistemology of scientific illustration', in B. S. Baigre (ed.), *Picturing knowledge: Historical and philosophical problems concerning the use of art in science,* University of Toronto Press, 1996, pp. 215-249.
[14] F. R. Wilson, *The Hand*, Vintage Books, 1998.
[15] G. Kaufmann, 'Imagery effects on problem solving', In P.J. Hampson, D. F. Marks, & J. T. E Richardson (Eds.), *Imagery: Current developments*. Routledge, 1990, pp. 169-197.
[16] L. Perini, 'Explanation in two dimensions: Diagrams and biological explanation', *Biology and Philosophy,* 20, 2003, 257-269.