ARTICLE
Vision and Art: An Interdisciplinary Approach to Neuroscience Education

Rosa Lafer-Sousa and Bevil R. Conway
Neuroscience Program, Wellesley College, Wellesley MA 02481

Undergraduate institutions are increasingly adopting neuroscience within their curricula, although it is unclear how best to implement this material given the interdisciplinary nature of the field, which requires knowledge of basic physics, chemistry, biology and psychology. This difficulty is compounded by declines over recent decades in the amount of physics education that students receive in high school, which hinders students' ability to grasp basic principles of neuroscience. Here we discuss our experiences as teacher (BRC) and student (RLS) with an undergraduate course in *Vision and Art*. The course capitalizes on students' prior interest in visual art to motivate an understanding of the physiological and computational neural processes that underlie vision; our aim is that the learning strategies that students acquire as a result of the format and interdisciplinary approach of the course will increase students' critical thinking skills and benefit them as they pursue other domains of inquiry. The course includes both expert lectures on central themes of vision along with a problem-based learning (PBL) laboratory component that directly engages the students as empirical scientists. We outline the syllabus, the motivation for using PBL, and describe a number of hands-on laboratory exercises, many of which require only inexpensive and readily available equipment. We have developed a website that we hope will facilitate student-driven inquiry beyond the classroom and foster inter-institutional collaboration in this endeavor. We conclude the paper with a discussion of the potential limitations of the course and how to evaluate the success of the course and the website.

Key words: Problem-Based Learning, Systems Neuroscience, Computational Neuroscience, Visual Neuroscience, Undergraduate Science Education; Physics Education

OVERVIEW

The interface between vision and art is an emerging interdisciplinary field with two goals: first, to examine art in order to shape hypotheses about how our brains process visual information; and second, to use information about neural processing to inform our understanding of art and the practice of making art. The field bridges physics, physiology, neurobiology, perception, psychology, philosophy, art history and studio art. The *Vision and Art* course at Wellesley College creates a learner-centered environment where students engage directly with this material through laboratory exercises, interactive lectures and discussions, class field trips, and independent student projects. The course is composed of students from diverse backgrounds and across the campus, which demands advanced communication and group-work skills that enrich the course experience for everyone.

The course consists of thirteen lectures on topics including optics; functional anatomy of the visual system; the receptive field; parallel and serial processing; central and peripheral vision; extrastriate specializations for color, faces and motion; neural representations of color, form, depth and motion; synestheisia and aesthetics. These are supplemented by two lectures providing an overview of Western Art (using Gombrich's *Story of Art* as a text) and ten sessions in which students lead in-depth discussions of important original research articles. In addition, the students engage in hands-on problem-based learning exercises that take place during eleven laboratory sessions. Students dissect a cow eye; measure the refractive power of the cow-eye lens; investigate the relationship between brightness and luminance; measure eye movements; make stereograms and pin-hole cameras; evaluate the spectral content of various illuminants; and test color judgments and color memory. They also participate directly in the practice of art in three sessions—two life drawing sessions and one still-life painting session, and complete eight major assignments including lab reports and formal analyses of artworks.

Why Problem-based learning?

To express his dismay with the condition of education during his youth, Albert Einstein spoke out against rote learning, a technique which forgoes understanding in exchange for memorization, arguing that the approach diminishes the spirit of learning and creative thought. He declared that you must "never memorize something that you can look up" (Ward, 2005). Rote learning still holds a valuable place in the mastery of certain foundational knowledge, but as information becomes increasingly well organized and accessible (especially with the rise of the Internet), the traditional educational emphasis on assimilating factual knowledge is shifting to an emphasis on understanding how to mine, assimilate, analyze and apply such knowledge to identify and solve problems. A goal of contemporary science education is to develop skills that transfer beyond the specific domain in which they are learned (Detmer, 1997). Equipping learners with problem-solving skills enables students to adapt within their unique career paths and make life-long contributions (Bransford et al., 2000). Further, the practice of problem solving promotes deeper understanding than does simple

exposure to factual knowledge (Bransford et al., 2000; Mazur, 2009).   The National Research Council's Committee on Developments in the Science of Learning argues that "Ideas are best introduced when students see a need or reason for their use—this helps them see relevant uses of knowledge to make sense of what they are learning." (Bransford et al., 2000).

In problem-based learning, students work together to solve open-ended problems while monitoring their own experiences. In this setting the instructor is a facilitator, whose guidance diminishes over time as students develop self-directed learning skills and confidence in their understanding of the material (Merrill, 2002). The strategy relies on Jean Piaget's constructivist theory, which holds that people generate knowledge and meaning from their experiences (Piaget, 1967).   Learning theorist Jerome Bruner (1961) explains that "Practice in discovering for oneself teaches one to acquire information in a way that makes that information more readily viable in problem solving." In shifting the responsibility for learning from teacher to learner it is important to consider the role of motivation, often the ultimate determinant of what a student gets out of her educational experience.

Intrinsic motivation arises when individuals want to do something because it brings them immediate satisfaction, or because they find the activity to be valuable and significant in its own right, or because the activity is perceived as moving them towards a goal that they themselves have set.   Extrinsic motivation involves external factors such as a desire for peer, parental, or institutional approval (or avoidance of disapproval), or tangible external rewards, such as wages. The distinctions between these two forms of motivation are not always separable. A student may want to achieve a high grade in a course as a satisfying and confidence-building affirmation of her mastery, as well as because she seeks a teacher's approval or an improved GPA to show potential employers or graduate or medical schools. However, when motivation is purely extrinsic and learning is perceived to be an imposition undertaken solely to please others or to secure tangible rewards then the process of learning will be impeded and much of what is 'learned' will not be retained. Von Glasersfeld (1889) argued that sustained intrinsic learner motivation depends on the learner's confidence in her potential for learning.   First-hand mastery of challenging problems generates such confidence, and with a vigor unmatched by any form of external acknowledgement (Prawat and Floden, 1994).   Further cultivation of such confidence can be achieved by involving the learner in the ongoing planning and evaluation of her instruction, as well as the instruction of her peers. Research on metacognition—"the ability to monitor one's current level of understanding and decide when it is not adequate"—suggests that learners can be taught to define their learning goals and monitor their learning process (Bransford et al., 2000).

Learners come "to formal education with a range of prior knowledge, skills, beliefs and concepts. This affects what learners notice, how they reason and solve problems, and how they remember" (Bransford et al., 2000).

Problem-based learning environments take into consideration the uniqueness of the learner as a fundamental part of the learning process, acknowledging, encouraging, and exploiting the complexity and multidimensionality of each participant (Wertsch, 1985). In fact, most analyses stress the importance of collaboration among learners (Duffy and Jonassen, 1992).   To be effective, the instructor must be sensitive to this diversity and create a framework for integrating such preexisting knowledge into the curriculum.

The interdisciplinary nature of the emerging field of Vision and Art lends itself naturally to problem-based learning; students come to the classroom with backgrounds ranging from art to science, each bringing something valuable to offer her peers and the course at large; and the interface of visual neuroscience and art is fertile with problems to be solved.

For example, by considering the problems faced by artists in rendering color, the students dig more deeply into what color is—they explore the physics of light and discover for themselves the deficiencies of a physical description of color. They eventually conclude that a full account requires an understanding of neural mechanisms. Through hands-on exercises, the students explore how object salience can be altered by manipulating foreground and background colors, and then investigate what necessary computations must exist in the brain to account for the phenomena they observe.

Welcome to the sandbox
The course is organized into a series of weekly lecture and lab sessions. Because class size is limited to about a dozen students, lecture sessions (2x per week) are intimate and discussion heavy, consisting of either instructor presentations pitted with conceptual problem-solving opportunities, or student-run journal clubs, where a student presents a journal article and leads a discussion. The goal of these sessions is to equip the students with the necessary background knowledge required to address potential problems relevant to the material covered in the laboratory that week. The lecture sessions are essential: despite overwhelming advantages to PBL, one potential drawback of this system when used exclusively is that students suffer debilitating gaps in knowledge and occasionally view themselves as less well prepared than students who have received conventional training (Albanese and Mitchell, 1993).

The lab sessions held each week amount to three and a half hours of loosely structured rigorous experimentation driven by an atmosphere of spirited inquiry, rather than the execution of neat pre-packaged protocols driven by the goal of specific results. More often than not, students do not know what the results of a given experiment "should" be.   Instead, progress is achieved by asking probing questions and designing clever experiments. Questions directed at the instructor are always met with more questions, as students are encouraged to dig deep and find answers they did not know they had access to. When answers remain elusive, students are encouraged to go home, look things up, and report back to the class. In this

way, students become active participants in the design of their daily assignments and overall educational trajectory. The students have referred to the lab as a schoolyard "sandbox." Each week a new set of toys is provided rather than a new set of instructions. The nature of these toys and the unique group of students at play have proven sufficient to generate substantial self-directed goals. Some of the laboratory exercises are described below.

Term Projects

In addition to lectures and weekly laboratory projects, students must develop in greater depth an empirical term project of their own design. Working with the course instructor, the students formulate a question, design and execute an experiment, analyze the data they acquire, present their results to their classmates and write a scientific report. While the goal is not to produce publishable results, one student in the first offering of the course produced an original project investigating the impact of drawing on size constancy that yielded an original finding which the student has been invited to submit for peer-review publication in *Perception*. Our hope is that this approach to undergraduate science education will yield a new generation of scientists capable of creative, interdisciplinary thought.
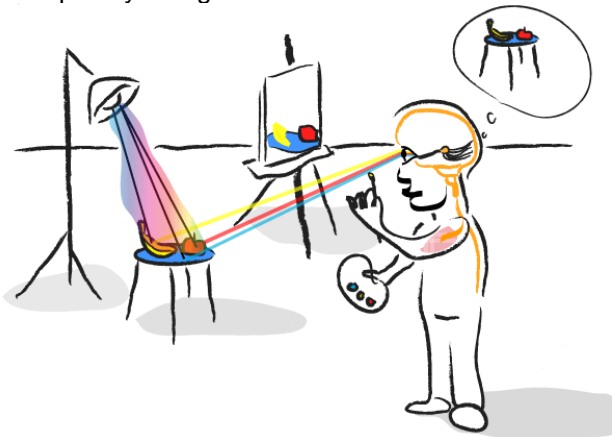

Figure 1. Vision and Art: Physics, Physiology, Perception, and Practice, course website graphic. This schematic maps our interdisciplinary approach, from the study of light (physics of optics) to eye and brain (physiology), to what we *see* (perception), and finally, to making art (practice). http://www.wellesley.edu/Neuroscience/Neuro320/

Digging from both ends of the tunnel

The goal of visual neuroscience is to understand how external light stimuli are received by the eye, processed by the brain, integrated with the internal state of the viewer and ultimately constructed into a perception, decision or action. Some disciplines, like psychology and philosophy, make progress on understanding vision by digging from the perceptual or cognitive end of the tunnel; other disciplines, like visual neurobiology, tackle the problem by digging from the other end of the tunnel, starting with the retinal signals. Outlined below are a handful of exercises and student projects that illustrate how each of these multiple disciplines is handled in this interdisciplinary approach (Fig. 1).

Physics

A given perception depends on the spectral composition of the illuminating light, the physical structure of the object, the local visual context, and the spatial resolution. All of these issues concern the artist making art and the scientist studying vision. But to gain an intuitive grasp of how the visual system obtains and processes information, the nature of the sensory stimulus itself—light—must be examined. Light travels in the form of electromagnetic waves—self-propagating oscillations of perpendicular electric and magnetic fields. Depending on the molecular structure of the objects they encounter, these waves are absorbed or reflected. Reflected light enters the eye, where it is focused on an array of about 125 million photoreceptors in the retina that generate neural responses when their wavelength-specific light-absorbing pigments absorb light. Those neural signals travel down the optic nerve to subsequent stages of the visual system.

The physical principles that govern how light interacts with the visual system are investigated in several lab activities: a cow-eye dissection and subsequent examination of its lens properties using light sources and an optic bench; the fashioning of pinhole cameras to study optics (Fig. 2); and the use of a spectroradiometer (PR-655 SpectraScan, Chatsworth, CA) in the assessment of perceptual judgments of achromatic brightness gradients (the relationship between luminance and brightness) and the measurement of the spectral composition of different common light sources.

Figure 2. Picture of a stuffed sloth taken by a student with a pinhole camera made with household materials during a lab activity. To review the principles of optics, students design and build pinhole cameras from materials they bring to class. They grapple with questions such as: Why is the projected image upside down? What governs exposure time? And how do you determine your camera's focal length? Photograph by Sophia Nora Giordano.

Physiology

Visual neurophysiologists attempt to understand the neural computations that underlie perception. They begin their work in the eye and follow the retinal signals through the optic nerve to the lateral geniculate nucleus (LGN) in the thalamus, a six-layered neural switchboard that routes information to the primary visual cortex (V1). From V1, visual signals are further processed by visual area 2 (V2) and then parceled out to a number of other extrastriate visual areas, each of whose functions are currently the focus of active research.

Other phenomena require more elaborate explanations for which we do not yet have a complete neurophysiological account. These phenomena usually require an understanding of the perceptual experience of the viewer: why are faces more recognizable when they
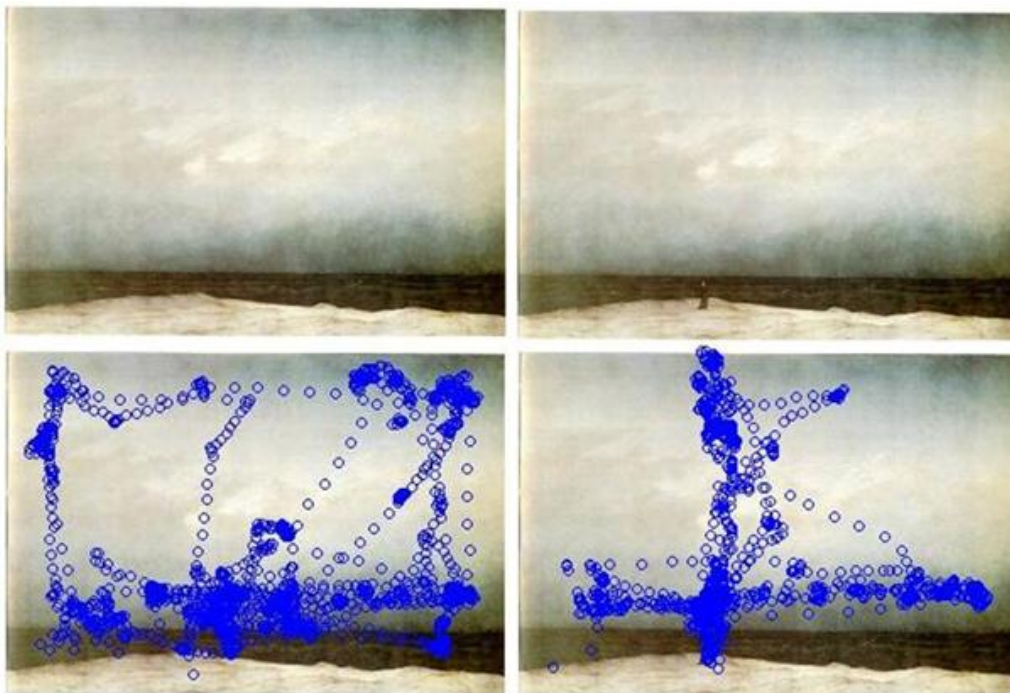
Figure 3. Eye position data (blue dots) from eye-tracking lab. The upper left panel shows a digitally manipulated version of Casper David Friedrich's, Monk by the Sea from 1809 (the monk is removed), which was shown to subjects before they were shown the original (upper right). The viewer's gaze was recorded for 30 seconds and overlaid (lower panels). The percent of time spent gazing at the picture quadrant associated with the monk increased over six-fold when the figure was included. The pattern of eye movements was also more globally affected: the eye position was restricted to a position of the sky presumably corresponding to where the monk was looking, suggesting that the viewer is experiencing the scene seen by the monk.

are right-side up? Why do we automatically assume that light sources are coming from above? Why do painted shadows have to be relatively darker to be interpreted as shadows? Why is blue the predominant favorite color? Why does imagining yourself as residing inside the world depicted in a canvas deepen your experience of the artwork?

By considering more deeply our responses to visual stimuli, including artworks, we become aware of, and learn to describe and characterize these phenomena, bringing us closer to the goal of defining the neural computations that bring these perceptual states about.

One means of studying our responses to visual stimuli is eye-tracking. An eye-tracker is a device that records a subject's point of gaze during a given visual task. Our visual acuity is not homogenous across the visual field (you can convince yourself of this by trying to read this text without moving your eyes), so we must move our eyes to bring objects into the center of gaze (the fovea). This process is effortless, usually unconscious, and can reveal useful insights. What kind of objects do we direct our gaze towards and how do artists take advantage of this when they compose a painting?

During the course, students perform a series of eye tracking experiments using an infrared eye tracker and custom software developed by ISCAN (iscaninc.com). This device works by shining an infrared (IR) beam onto the subject's eye while she looks at an image with her head resting on a chin rest. A camera is trained on her eye and detects the reflection of the IR beam from her cornea. The camera also detects the reflectance "hole" of the pupil. The corneal reflection, which indicates head position, and the pupil, which indicate eye position, are recorded and after appropriate calibration can be used to directly determine the subject's eye position.

In the first part of the lab the students track each other's eye movements during a simple voluntary saccade task and smooth pursuit task. They then use computer software (Matlab) to evaluate the saccade latencies for each task. The students discover that human eye movements differ depending on the task at hand, often in surprising ways. The extent to which the task at hand influences an observer's visual investigation was demonstrated most famously in the 1950s by Russian psychologist Alfred L. Yarbus who wrote that "eye movements reflect the human thought processes; so the observer's thought may be followed to some extent from records of eye movements (the thought accompanying the examination of the particular object). It is easy to determine from these records which elements attract the observer's eye (and, consequently, his thought), in what order, and how often" (1967).

In the second part of the lab students study their own saccadic eye movements as they look at reproductions of four paintings of natural scenes with contemplative figures, as well as four versions of the paintings digitally manipulated to remove the figures. (This exercise is a "seed" experiment: students are encouraged to engage in further exploration using images they acquire.) The students are not provided with a rationale for this experiment. The experimental design is intended to prompt the students to examine eye movements in closer detail, and to begin to formulate scientific questions themselves. Importantly, there is no "right answer," and by omitting a goal for specific results we hope to shift focus to the practice of science rather than the product. In short, our goal is to create the conditions for students to discover a problem, and then provide them with the tools to tackle

the problem. A sample of data collected is shown in Figure 3. Not surprisingly, students arrived at many of the same conclusions elucidated in prior studies of visual attention. Several students even made the association between visual attention, eye movements and Theory of Mind (see Fig. 3). But most importantly, the students generated novel questions and methods of analysis.

Perception

Visual neuroscience has been profoundly informed by the products and practice of artists; indeed artists themselves have often made significant contributions to our understanding of how the visual system functions, both in terms of the basic mechanisms of visual neurobiology and in terms of higher-order processes of psychology (Cavanagh, 2005; Conway and Livingstone, 2007; Mamassian, 2008). The marks most artists make are fundamentally constrained by the kinds of computations performed by the visual system, and thus reflect aspects of how the visual system is wired. Visual artists employ an array of optical tricks to construct illusions of depth, color, light and form; and to guide visual attention or evoke emotional responses. While it is clear artists have been studying visual phenomena far longer than neurobiologists, their understanding of visual processes is largely intuitive. Our goal is to use the study of art and art making to identify this intuitively derived understanding, and in turn design creative experiments to determine its physiological underpinning. To cultivate the skills needed to identify visual phenomena, students visit galleries and write formal analyses of art works—writings that address how the artist employs the formal visual elements (line, shape, color, composition, etc.) to express the subject matter. They then explore such phenomena through hands-on activities.

For example, students investigate the perceptual significance of low-spatial frequency versus high-spatial frequency stimuli and the functional role of foveal versus peripheral vision in an assignment inspired by Leonardo Da Vinci's *Mona Lisa*. Da Vinci demonstrated a profound intuitive sense for how low spatial frequency information communicates important information about emotional states in a way that high spatial frequency does not (Livingstone, 2000; Vuilleumier et al., 2003).

As part of a laboratory experiment students take two digital photographs of the same person sitting perfectly still under neutral lighting conditions against a neutral background with a camera positioned at the same viewing angle. In one photograph the subject makes a neutral (unsmiling) expression. In the second photograph the subject makes a broad smile. The first photograph is passed through a high-spatial frequency filter, and the second through a low spatial frequency filter, whose parameters are determined by the student through experimentation. The images are merged (Fig. 4) and examined at a number of viewing distances. In addition, at a relatively close viewing distance the subject's expression is examined as the viewer's gaze is shifted systematically across the image, from the eyes to the mouth. In this way the students reproduce the elusive Mona Lisa smile. The students are asked to examine the ways in which naïve subjects often depict emotional expression (e.g. using smiley faces), versus the ways in which artists often do. Why are lines ultimately less effective at communicating expression than *sfumato* (wikipedia.org/wiki/Sfumato)? A *severely* smiling face, depicted with lines, starts to look like it is old and grimacing, rather than happy.

Through student-directed inquiry, the students uncover an understanding of the neural basis for the Mona Lisa effect. They use their knowledge of the visual system, along with their nascent problem-solving skills to uncover an explanation and avenues for further research. They determine that the organization of the retina accounts for much of this "Mona Lisa" effect: the periphery of your visual field is sampled by a lower concentration of photoreceptors and a higher degree of photoreceptor pooling by ganglion cells, and as such is specialized to detect low-spatial frequencies (coarse information). The fovea, on the other hand, contains a higher density of photoreceptors and a photoreceptor-to-ganglion cell ratio close to unity; it is thus specialized for high-spatial frequencies (fine details). Da Vinci painted Mona Lisa's smile using shadows that are detected best by our peripheral vision. Consequently, when a viewer's gaze is directed away from the mouth, such as at the eyes, the

Figure 4. Student's "Mona-Lisa Effect" experiment. Smiling and neutral expression images were passed through low and high-spatial frequency filters respectively. The merged image is shown. When viewed closely or from a distance, the image appears to alternate, respectively, between the neutral and smiling expressions. The same phenomenon occurs when, at a close viewing, the observer shifts her gaze between the eyes (smiling) and the mouth (not smiling). Image courtesy of Sang-Hee Min and Marlie Philiossaint.

smile becomes apparent, but the moment the mouth is brought into the fovea it retreats.

Practice
By getting directly involved in studio practice—making art!—students develop an intuition for the "tricks" of the artist, helping make tangible much of what we know about how the visual system works, and bringing into focus many of the mysteries.   Accordingly, studio sessions and subsequent critiques play an integral role in the course.

Some students express concern with their lack of experience, but the mistakes common to inexperienced artists prove particularly useful for classroom discussion (provided all the students are comfortable). The students discover that the visual experience of a work in progress is fundamentally different from that of a final product. How does the way we process visual information shape art practice? The artist is charged with making a stimulus for consumption by the visual system of another person, yet must do so having access only to the products of their own visual system.   If we consider the visual system as a processor of information, it is as if artists must provide the raw materials to the processors of viewers yet only have access to the processed product of their own system. Anya Hurlbert has discussed how this problem poses a particular challenge in capturing color constancy using Monet's Rouen Cathedral paintings as examples (Hurlbert, 2007). The result of this dilemma is manifest as common errors in naïve drawings; and the errors therefore provide insight into how our brains are handling visual information.

Figure 5. Drawing samples from life drawing studio session. A given retinal ganglion cell measures the pattern of brightness (relative luminance) across its receptive field rather than the absolute value of light falling on it (luminance), making our visual system much more sensitive to local changes across the visual field, such as edges, than gradual ones. As a result, we spend more time looking at edges and students tend to overwork marks demarcating edges.

For example, because edges are detected as discontinuities in brightness, due to the center-surround organization of visual receptive fields, people tend to spend more time looking at edges, and consequently tend to overwork marks representing edges (Fig. 5). Many visual modalities, including color, depth, motion, and luminance show much greater sensitivity to local changes across the visual field than gradual ones—it is these regions of

change that carry the most useful information because they demarcate object boundaries, which are most deserving of our visual attention.

Inspired by her studio experience, a student in the course, Colleen Kirkhart, investigated a common drawing mistake caused by shape constancy. When faced with the task of drawing a cup or a bowl from the side, inexperienced students tend to render the top as more circular than they ought to be (Fig. 6). The student *knows* the object itself is circular and draws it as such, despite the fact that the retinal projection is of a narrow ellipse.

Figure 6. Shape constancy. A drawing of the pictured stimulus exaggerates certain features.

Beginning drawing instructors always remind their students to "draw what you see, not what you know." Much training and even more looking is required to overcome the tendency to make this common drawing mistake. Kirkhart wanted to know if this problem arose because of a perceptual distortion. That is, does the individual *see* the form as more circular than it is? This raised an interesting question as to what it means to *see* in contrast to what it means to *perceive*. And what does *knowing* have to do with it?

These questions were examined by comparing the degree of shape constancy exhibited by subjects performing both a drawing task and a digital matching task (using a GUI Kirkhart written with Matlab).   Subjects viewed four different classes of stimuli, and were asked to either draw the object by hand or use a computer to generate a shape that matched that of the stimulus. The degree of distortion was calculated by comparing the ratio of the horizontal and vertical axes of the subject response and the actual object. Both reporting techniques produced errors, but the drawing error was significantly larger. These results suggest that a process beyond simple perceptual distortion may be responsible for common errors in drawing.

EVALUATION
As enthusiasm for undergraduate neuroscience education increases, so too does the demand for adequate assessment tools for evaluating neuroscience courses. In order to successfully evaluate our course it is useful to pin down what we consider to be the specific goals of the course and the methods of instruction. The course goals are:
1. Facilitate inter-departmental study across campus
2. Foster creative interdisciplinary thought
3. Promote the ethical use of neuroscientific data in fields outside of scientific research
4. Develop an ability to read and critically evaluate the scientific literature

5. Acquire confidence and fluency with oral and written communication
6. Promote scientific research
7. Improve problem-solving skills

The methods of instruction take advantage of both PBL and interactive lectures given by experts. "Today's information community expects graduates not only to have a specific knowledge base but also to be able to apply this knowledge to solve complex problems in an efficient way" (Dochy et al., 2003). This demands flexibility and transferable skills, those skills that PBL proposes to cultivate. "Educational practices have been criticized for not developing these prerequisites of professional expertise" (Dochy et al., 2003). To meet these needs PBL is being used with increasing frequency in a diverse range of environments, including undergraduate science courses, medical schools and professional programs (Ribeiro, 2008). The challenge is to establish mechanisms for evaluating the efficacy of this combined pedagogical approach in the context of the goals outlined above.

As a backdrop for our course-specific evaluation it has been important to maintain a global perspective on the necessity and efficacy of learner-centered PBL environments in general. Since its inception four decades ago, much research has been conducted on PBL in real classrooms. Harvard Physics Professor Eric Mazur, who has implemented a learner-centered PBL brand of teaching in his classroom reports, "Data obtained in my class and in classes of colleagues worldwide, in a wide range of academic settings and a wide range of disciplines, show that learning gains nearly triple with an approach that focuses on the student and on interactive learning" (Fagen et al., 2002; Lasry et al., 2008; Mazur, 2009). A recent statistical meta-analysis review of 43 empirical studies on PBL in tertiary education also found a substantial positive influence of PBL on the skills of students (knowledge application), and a weaker, though still positive, effect on knowledge acquisition, with some studies, particularly in the sciences, showing a small favor for lecture over PBL (Dochy et al., 2003). But where studies found that students acquired slightly less knowledge, students were shown to have retained more of the acquired knowledge in the long run and the reported disparities in acquisition "disappear if the reproduction of knowledge is assessed in a broader context that asks all the students to apply their knowledge" (Dochy et al., 2003), a finding that calls into question how we ought to go about assessing knowledge acquisition. Assessment strategies range from free recall tasks in which students are asked to write down everything they can recollect about a particular topic to performance-based testing which assesses higher cognitive functions in addition to knowledge (Dochy, 2003).

Critics argue that the abstraction of knowledge that occurs during problem-solving is largely responsible for the reported reduction in knowledge acquisition (Albanese and Mitchell, 1993; Segers et al., 2003) and that self-directed learning is often poorly developed because students are expected to "learn by doing what they do, when they do not know how to do what they have to learn," a seemingly paradoxical task (Segers et al., 2003). Learning to master problem-solving and college level material, and do each by way of the other does pose a real challenge. Students tend to get frustrated if given too little direction early on in PBL courses (Segers, 2003). Successful courses typically rely on both a balance between lecture and PBL, to prevent disparities in knowledge acquisition and student confidence (Ribeiro, 2008; Mazur 2009), as well as more extensive instructor involvement initially, with instructor-guided problem-solving activities, and diminishes over time, building to more open-ended self-directed problem-solving tasks (Segers, 2003). Accordingly, this is the approach we take with the Vision and Art course at Wellesley.

For our course-specific evaluation we intend to incorporate the opinions of students, Wellesley faculty and external panels in evaluating the course. The small class sizes at Wellesley allow us to provide focused attention on each student. Student evaluation questionnaires will be administered at the beginning, middle and end of the course to track the students' own perceptions of their learning, a tactic commonly employed in places where PBL is being implemented (Albanese and Mitchell, 1993). We will also maintain a database of former students to poll student reflections of their learning in the context of post-graduation careers.

We will track enrollment and waitlists in the course and the number of recruits to the Neuroscience Major at the College. In an effort to evaluate the success of the course regarding facilitating inter-departmental study, we will keep track of the number of students registered in the course from different backgrounds and majors. We will keep track of student performance on examinations and attempt to correlate performance with student major. We will continue to broaden the involvement of faculty from departments outside of neuroscience across the college, specifically art and physics faculty. Our hope is to eventually have the course cross-listed within these relevant departments. We will also track application and acceptance rates to professional and graduate programs.

We have established a course website, through which we hope to solicit feedback from the wider community, and to disseminate course materials to institutions interested in developing similar programs. The course website is: http://www.wellesley.edu/Neuroscience/Neuro320/. Through this website we also hope to solicit advice about appropriate mechanisms for evaluation.

Finally, we intend to host a team of external evaluators from undergraduate institutions with strong neuroscience programs (e.g. Davidson, Smith, and Oberlin Colleges). This visit will enable us to exchange information about challenges of undergraduate neuroscience education and to disseminate ideas about successful solutions.

Student Perspective of the Course
One of us (RLS) was a student in the first semester this course was offered. She co-wrote the article and contributed to the design of the revised curriculum we describe. Here is a brief summary, in the student's voice, of her experience taking the course.

After five semesters at Wellesley and a lifetime of aspiration to practice science, what I considered to be an endlessly creative and satisfying pursuit, I had grown

discouraged with the state of science education and was losing momentum. The Vision and Art course left me invigorated with an enthusiasm I had not felt since first arriving at Wellesley. I naturally developed a personal ownership over my learning experience that compelled me to read and write and contemplate the material above and beyond my own expectations. A year has passed since then and my enthusiasm has not waned, but only grown as I continually discover new ways to apply my problem solving skills and passion for the material in my ongoing coursework, independent research (my involvement with which was the direct result of taking the course), and assistance in the organization and execution of this year's course offering.

REFERENCES

Albanese MA, Mitchell S (1993) Problem-based learning: a review of literature on its outcomes and implementation issues. Acad Med 68:52-81.

Bransford JD, Brown AL, Rodney R (eds) (2000) Committee on Developments in the Science of Learning, National Research Council. The design of learning environments. In: How people learn: brain, mind, experience and school, pp131-146. Washington, DC: National Academy Press.

Bruner JS (1961) The act of discovery. Harv Educ Rev 31:21–32.

Cavanagh P (2005) The artist as neuroscientist. Nature 434:301-307.

Conway BR, Livingstone MS (2007) Perspectives on science and art. Curr Opin Neurobiol 17:476-482.

Detmer DE (1997) Knowledge: a mountain or a stream? Science 275:1859-1860.

Dochy F, Segers M, Van den Bossche P, Gijbels D (2003) Effects of problem-based learning: a meta-analysis. Learning and Instruction 3:533-568.

Duffy TM, Jonassen D (eds) (1992) Constructivism and the technology of instruction: a conversation. Hillsdale NJ: Lawrence Erlbaum Associates.

Fagen AP, Crouch CH, Mazur E (2002) Peer Instruction: results from a range of classrooms. Phys Teach 40:206-209.

Hurlbert A (2007) Colour constancy. Curr Biol 17:R906-907.

Lasry N, Mazur E, Watkins J (2008) Peer instruction: from Harvard to the two-year college. Am J Phys 76:1066-1069.

Livingstone MS (2000) Is it warm? Is it real? Or just low spatial frequency? Science 290:1299.

Mamassian P (2008) Ambiguities and conventions in the perception of visual art. Vision Res 48:2143-2153.

Mazur E (2009) Education. Farewell, Lecture? Science 323:50-51.

Merrill MD (2002) A pebble-in-the-pond model for instructional design. Performance Improvement 41:39–44.

Piaget J (1967/1971) Biology and knowledge. Chicago, IL: University of Chicago Press.

Prawat RS, Floden RW (1994) Philosophical perspectives on constructivist views of learning. Educational Psychology 29:37-48.

Ribeiro LRC (2008) Electrical engineering students evaluate problem-based learning (PBL). Int J Elec Eng Educ 45:152-161.

Segers M, Van den Bossche P, Teunissen E (2003) Evaluating the effects of redesigning a problem-based learning environment. Stud Educ Eval 29:315-334.

von Glasersfeld E (1989) Constructivism in education. In: International Encyclopedia of Education (Husen T, Postlewaite N; eds), pp162-163. Oxford, England: Pergamon Press.

Vuilleumier P, Armony JL, Driver J, Dolan RJ (2003) Distinct spatial frequency sensitivities for processing faces and emotional expressions. Nat Neurosci 6:624-631.

Ward DW (2005) Physics the google way. Phys Teach 43:381-383.

Wertsch JV (1985) Vygotsky and the social formation of mind. Cambridge, MA: Harvard University Press.

Yarbus AL (1967) Eye movements and vision. (Translated from 1965 Russian edition by Basil Haigh.) New York, NY: Plenum Press.

Address correspondence to: Professor Bevil Conway, Neuroscience Program, Wellesley College, 106 Central Street, Wellesley MA, 02418 Email: bconway@wellesley.edu