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Article

Engagement and Skill Development in Biology Students through Analysis of Art

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An activity involving analysis of art in biology courses was designed with the goals of piquing undergraduates' curiosity, broadening the ways in which college students meaningfully engage with course content and concepts, and developing aspects of students' higher-level thinking skills, such as analysis, synthesis, and evaluation. To meet these learning outcomes, the activity had three key components: preparatory readings, firsthand visual analysis of art during a visit to an art museum, and communication of the analysis. Following a presentation on the methodology of visual analysis, students worked in small groups to examine through the disciplinary lens of biology a selection of approximately 12 original artworks related in some manner to love. The groups then developed and presented for class members a mini-exhibition of several pieces addressing one of two questions: 1) whether portrayals of love in art align with the growing understanding of the biology of love or 2) whether the bodily experience of love is universal or, alternatively, is culturally influenced, as is the experience of depression. Evaluation of quantitative and qualitative assessment data revealed that the assignment engaged students, supported development of higher-level thinking skills, and prompted meaningful engagement with course material.

INTRODUCTION

In designing or reworking a course, significant challenges arise beyond the choice of content to be covered. In particular, formulating activities that captivate students' interest and engage them with the material, while also promoting development of disciplinary skills, takes thought and creativity, as does aligning courses with the broader educational mission of the institution and with the recommendations of educational reform efforts. For example, many colleges and universities, as well as reports such as *Vision and Change in Undergraduate Biology Education: A Call to Action* (American Association for the Advancement of Science [AAAS], 2011), are prompting students to integrate their studies across disciplines and to think critically, creatively, and collaboratively. Such educational aims were the impetus for the class activity described in this report.

Influenced by constructivism, the assignment asked students, working in small groups in a museum setting, to examine through the disciplinary lens of biology a selection of original artworks related in some manner to love, particularly facets termed lust, romance, and stable pair-bonding. A biological understanding of love, although highly fragmentary now, is emerging (e.g., Fisher, 1998; Zeki, 2007). Following close examination of the artworks, the groups then crafted and presented for class members a temporary mini-exhibition of several pieces addressing one of two questions: 1) whether portrayals of love in art align with the growing understanding of the biology of love or 2) whether the bodily experience of love is universal or, alternatively, is culturally influenced, as is the experience of depression (e.g., Kleinman, 2004). These questions were relevant to the content of the two biology courses at Oberlin College in which the activity has been used as a capstone experience and assessed quantitatively and qualitatively: 1) an upper-level class on animal physiology and 2) a limited-enrollment course that is

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part of a program of seminars for first-year students. In the former, the project served as a window to the humanities, one prompting majors to look outwardly from the discipline and to make connections between biology and other areas of study. In the seminar, the project offered a window to biology, one intended to spark interest in the field by showing its relevance to students' daily lives. With a similar aim, a modified version of the activity, involving the visit to the class by a museum curator and projection of images of artworks, was offered without assessment in the first semester of the introductory sequence to the biology major, a class with enrollment of 143 students. In each of these cases, the art activity had as its primary purpose the intellectual engagement of students, not coverage of particular biological content.

Additionally, the art activity sought to develop in students thinking skills, such as analysis, synthesis, and evaluation. To do this, the project used art to create an opportunity for students to grapple with ambiguity—to analyze portrayals of love rigorously through the disciplinary lens of biology, to take stock of biases and limitations in interpreting the images, and to defend in writing and oral presentation their reasoning from premise to conclusion. Close visual analysis of art, in combination with discussion of observations and interpretations among peers, promotes growth of critical thinking, which importantly is transferred to other content areas and social contexts (Housen, 2001–2002). This transferability, along with the importance of visual analysis in clinical medicine, has provided the rationale for inclusion of art analysis in the curricula of a number of medical schools (for review, see Perry *et al.*, 2011). In contrast to medical schools, undergraduate programs in the life sciences do not typically include art analysis, and published descriptions of ways to incorporate it in an undergraduate life-sciences program are rare. The present report sought to fill this gap.

Examining the implementation of an art-based activity in an undergraduate biological curriculum, this study addressed two questions:

1. whether gains in visual analytical ability could be achieved through an art-based activity of limited duration, namely 2.5–3 h, that is, the time typically allotted for one laboratory session or several class periods and
2. whether students in biology courses would find the art-based activity engaging, meaningful, and thought-provoking.

The first question has practical importance because undergraduate programs could more readily adopt an art-based activity designed as a module of several hours duration, rather than as a stand-alone course involving 10 or more hours of contact time with art, as is common in medical curricula. The significance of the second question is twofold. Success of the project as a learning activity, from a constructivist vantage, hinged on intellectually engaging students (Dewey, 1913; Julyan and Duckworth, 1996). Such engagement, moreover, directly addresses one of the most common concerns of students of science, both those who persist in science majors and those who switch to majors outside the sciences, namely, loss of interest in science stemming from classes lacking sufficient intellectual stimulation (Seymour and Hewitt, 1997). Whether biology undergraduates would find an art-based activity engaging and valuable, however, was uncertain. Thus, through the second question, the study probed the students' subjective experience of the activity, with emphasis on whether it piqued undergraduates' curiosity and provoked thought. In addressing these two questions, the study relied on a balanced assessment scheme, one based on quantitative and qualitative methods.

METHODS

Participants and Context

Oberlin College is a private, selective liberal arts institution comprising a College of Arts and Sciences offering the BA (enrollment 2371 in Fall 2012) and a Conservatory of Music offering the BM (enrollment 372 in Fall 2012). Oberlin also offers a 5-yr, double-degree program (enrollment 187 in Fall 2012) that awards both the BA and the BM. Assessment data were collected in two courses: a limited-enrollment (maximum 16) seminar for first-year undergraduates (FYSP 182, The Body in Health and Disease) in its 2011 and 2012 offerings, and an upper-level class within the biology department (Biology 312, Animal Physiology) in its six offerings since 2008. Of the 30 students who enrolled in the two offerings of the seminar, 40% were female and 60% were male; 73% were Caucasian, 10% were Latino/a, 3% were African American, 7% were Asian American, and 7% were international students. Because the undergraduates took the seminar in their first semester of college, they had not yet declared a major. Of the 144 students who enrolled in the six offerings of Animal Physiology, the demographics were as follows: 65% female and 35% male; 74% Caucasian, 13% Asian American, 4% African American, 4% Latino/a, and 5% international students; 83% fourth- or fifth-year students (some students were pursuing the 5-yr BA/BM double-degree program), 16% third-year students, and 1% second-year students. The majors represented among the Animal Physiology students included biology (77%), neuroscience (12%), musical performance (8%), biochemistry (8%), and, at $< 5\%$, a broad span of other disciplines, ranging from creative writing to sociology and dance to religion. Note that Oberlin students commonly pursue more than one major; hence, the percentages pertaining to majors exceed 100.

Project Description

The art activity had three key components, each of which centered on students working in small groups: discussion of preparative readings; visual analysis of the artworks themselves during a visit to Oberlin College's Allen Memorial Art Museum (AMAM); and communication of the analysis to other members of the class, the course instructor, and a museum curator. These components are elaborated upon subsequently.

The preparatory readings (Table 1), in combination with group-based discussion of them in class prior to the museum visit, helped to establish a common intellectual foundation. Several introduced students to the emerging, albeit fragmentary understanding of the neuroendocrine basis of love (Szalavitz, 2002; Anderson and Middleton, 2006; Zeki, 2007), as well as to the comparatively more established ideas concerning the biological basis of anxiety and depression (Brown, 2003). For example, brain regions activated during

Table 1. Preparative readings used in one or more offerings of the art project

Anderson A, Middleton L (2006). What is this thing called love? New Sci *190*, 32–34.
Anonymous (1874). In the laboratory with Agassiz. Every Saturday: A Journal of Choice Reading *4 April 1874*, 1, 14. [Authored by Samuel Scudder.]
Brown P (2003). In the shadow of fear. New Sci *179*, 30–35.
Cannon WB (1928). The mechanism of emotional disturbance of bodily functions. N Engl J Med *198*, 877–884.
Cannon WB (1934). The significance of the emotional level. Sci Mon *38*, 101–110.
Kleinman A (1977). Depression, somatization and the "new cross-cultural psychiatry." Soc Sci Med *11*, 3–10.
Ots T (1990). The angry liver, the anxious heart and the melancholy spleen. Cult Med Psychiatry *14*, 21–58.
Phillips H (2003). The pleasure seekers. New Sci *180*, 36–40.
Szalavitz M (2002). Love is the drug. New Sci *176*, 38–40.
Zeki S (2007). The neurobiology of love. FEBS Lett *581*, 2575–2579.

early stages of love overlap with the brain's reward circuitry, activated when drugs such as cocaine are ingested; moreover, early stages of love are associated with altered levels of chemicals such as dopamine, serotonin, and oxytocin (reviewed by Zeki, 2007). Other readings (especially Kleinman, 1977; Ots, 1990) developed the notion of somatization, as exemplified by the typically physical experience of depression (e.g., abdominal discomfort, blurred vision, or palpitations) in many parts of Chinese society, in contrast to the psychological experience characteristic of Western societies. That a specific linkage exists between emotions and bodily changes was further elaborated through study of the writings of Cannon (1928, 1934), which usefully placed the autonomic nervous system at the fore. In many respects, the autonomic nervous system, in mediating the bodily experience of emotions, served as the intellectual keystone for the art activity. Thus, the preparative readings, in keeping with the activity's role as an integrative capstone, built on topics previously treated in the courses, including sympathetic and parasympathetic modulation of bodily function as well as intercellular signaling via transmitters and hormones.

None of the preparative readings, however, defined the bodily changes elicited by love, and having students suggest changes correlating with lust, romance, and stable pair-bonding (i.e., with the three commonly accepted faces of love; e.g., see Fisher, 1998) served as a means for engaging students with the activity and piquing their curiosity. The undergraduates in Animal Physiology spent two class sessions on sexual physiology, studying the mechanisms behind vaginal lubrication and penile erection (class reading: Levin, 2003), as well as the cardiopulmonary response to coitus (class reading: Fox and Fox, 1969). Students therefore had been introduced to and were able to describe the physiological mechanisms behind bodily changes correlating with lust or sexual activity, but the students had to rely on experience and perhaps imagination regarding the bodily signals of romance and stable pair-bonding. Instructors wishing to direct students' thinking on bodily changes correlating with romance (i.e., passionate love) could refer students to Tennov (1979, especially pp. 48–50) and Hatfield and Sprecher (1986), who note changes such as palpitations, trembling, pallor, sweaty palms, and flushing.

The three faces of love (lust, romance, and stable pair-bonding) were reflected in the works from the AMAM's collection selected for study. These typically numbered approximately 12 per course, with one-quarter to one-half from the museum's Asian holdings (generally works from China, Japan, and India). The other works largely represented a range of genres of Western art (European or American). Table 2 lists the artworks that were used; images of most are available in the museum's digital repository (http://rubens.cc.oberlin.edu/emuseum). Each course worked with the original artworks in the museum for 1.5–3 h, and students were helped to engage with the project in at least two distinct ways. First, artworks were chosen with a view toward their accessibility and expressive content, that is, their ability to captivate and invite multiple readings or interpretations. Second, at the start of a class visit to view the artworks, a museum curator (C.C. or L.M.) and the course instructor (T.A.) described their approach to looking at a work of art and then guided analysis of an image. The guidance typically comprised questions designed to prompt students to observe fully and repeatedly and to use visual evidence to support claims about the work's message and content (e.g., What do you see? What is going on in this image? What is it that makes you think or say that? What more can you find? How does this work compare with that one? These questions, as well as others that were asked to prompt close observation, mindfulness, and curiosity, draw on the Visual Thinking Strategies elaborated by Housen [2001–2002], as well as the thinking dispositions palette described by Tishman and Palmer [2006]). The guidance, while giving direction to the students, drew them into the work. Also helping students to connect with the artworks and the project was the curator's reminding students simply to describe what they saw, rather than to couch their initial analysis in physiology, art history, or information about the artworks. Engagement likely also grew by the infectious enthusiasm of the students, with the ideas and curiosity of one nurturing the interest of others.

Students then worked in groups of three or four to analyze the artworks and to formulate for class members, course instructor, and museum curator a mini-exhibition of four works of the group's choosing to address one of two questions: 1) whether portrayals of love in art align with the growing understanding of the biology of love or 2) whether the bodily experience of love is universal or, alternatively, culturally influenced. Students sorted themselves into the groups of three or four, and students monitored themselves to ensure that all group members contributed comparably. The project ended with an oral presentation of each exhibition by each of the groups, either on the day of the visit or during a later visit, as described subsequently.

The nature of the visits with artworks evolved in three ways, largely in response to comments provided by students on the numerical survey of their impressions. First, beginning in 2010, guidance to students on visual analysis was expanded to include—prior to the museum visit—a class

Table 2. Original artworks used in the project[a]

Anonymous (Indian/Malwa): *Lovers* (1640–1660, opaque watercolor with ink and gold shell)
Anonymous (Utagawa Kunisada, Japanese): *Erotic Subjects Matched with Fans* (1830s–1840s, color woodblock print)
Anonymous (Japanese): *Young Man Offering to Help Clear a Woman's Shoe of Snow* (ca. 1770, color woodblock print)
Alexander Archipenko: *The Rape* (ca. 1934, charcoal)
Banki: *Shinguchimura no bosetsu, Evening Snow at Shinguchi Village, The Lovers Umegawa and Chubei* (ca. 1800, color woodblock print)
Max Beckmann: *The Dancers* (1922, woodcut)
Peter Behrens: *Der Kuss (The Kiss)* (1898, color woodcut)
Larry Clark: *Untitled,* from *Tulsa "40"* (1971, gelatin silver print)
Albrecht Dürer: *Abduction of Proserpina* (1516, etching)
Giorgio Ghisi: *Venus and Adonis* (1567–1573, engraving)
Nan Goldin: *Nan One Month After Being Battered* (1984, Cibachrome print)
Suzuki Harunobu: *Woman Throwing a Snowball at a Girl Reading a Love Letter* (1767–1769, color woodblock print)
Erich Heckel: *The Couple* (1923, woodcut)
Allen Jones: *Concerning Marriage, IV* (1964, lithograph)
Rockwell Kent: *The Lovers* (1928, wood engraving)
Ernst Ludwig Kirchner: *Union, from the series Man and Wife* (1900, woodcut)
Utagawa Kuniyoshi: *Tsumagome: Abe no Yasune Watching His Wife Change into a Fox-spirit, no. 43 from the series The Sixty-nine Stations of the Kisokaido Road* (1852, color woodblock print)
Roy Lichtenstein: *Study for Kiss II* (1963, graphite pencil on paper)
Okumura Masanobu: *Portrait of a Courtesan as a Love Letter* (ca. 1710, color woodblock print)
Edvard Munch: *The Sin (Nude)* (1902, color lithograph)
Rembrandt Harmensz van Rijn: *Rembrandt and Saskia* (1636, etching)
Rembrandt Harmensz van Rijn: *Joseph and Potiphar's Wife* (1634, etching)
Georges Rouault: *Prostitute* (1924–1927, lithograph)
Kitagawa Utamaro: *The Lovers Ohan and Choemon* (early 19th century, color woodblock print)
Holly Wright: *True Saints: Jesus and St. John* (1980–1984, gelatin silver print)
Tsukioka Yoshitoshi: *Portrait of a Courtesan* (1888, color woodblock print)

[a]The works (listed by artist and title) are held in Oberlin College's AMAM. In most cases, images are available in the museum's digital repository (http://rubens.cc.oberlin.edu/emuseum).

session led by a museum curator and focusing on composition, space, perspective, scale, light (shading), color, texture, and medium. These formal elements of an art object influence its visual message, which informs interpretation, regardless of disciplinary vantage (e.g., Barnet, 2008). Second, the amount of time students were given to examine and analyze the works was expanded by making images available online, both before the actual museum visit and afterward. Third, a postvisit assignment was initiated in 2009 in Animal Physiology. The assignment in 2009 called on each group of students to write approximately 300 words on the rationale for inclusion of the chosen works in the group's mini-exhibition. In 2010, the length of the composition was increased to approximately 1000 words, allowing for greater elaboration of visual and physiological analyses of the chosen works, an enhancement that yielded more substantive and thoughtful responses from the students. The 2011 and 2012 offerings of Animal Physiology and Body in Health and Disease likewise asked for compositions of this length. Illustrative of the students' analyses are the following two extracts from compositions by two groups in 2010. These extracts were selected from papers graded at the "A" level, reflective of rigorous analysis and effectiveness in using course material to support that analysis; additionally, the excerpts addressed artworks for which permissions to reproduce images of the artworks were obtainable. Figure 1 depicts the analyzed artworks:

> In *Union*, the faces of the figures are obscured, and the musculature of their bodies is constructed from sharply defined lines rather than subtle shading, texture, or color. These artistic choices seem to de-emphasize the unique identities of the subjects and contribute to an overall focus that is on the physical act of intercourse between two bodies … *The Lovers* (India) is very brightly colored. The two bodies, especially the male, have noticeably flushed skin, symbolizing the increased muscular and cardiovascular work of the bodies during intercourse. In *Union*, Kirchner [the artist] used dynamic lines (rather than color) in his construction of the human figures and in his stylized depictions of nature in order to emphasize the physical activity occurring in the scene. During periods of physical exertion, neuronal action potentials release ACh [acetylcholine] onto the skeletal muscles, causing a Na^+-based action potential in the muscle that ultimately results in calcium release from the sarcoplasmic reticulum. Increased myoplasmic calcium binds troponin-C, facilitating the binding of myosin to actin and resulting in increased muscular force. Because the power stroke of this myosin cross-bridge cycle is ATP-dependent, increased muscular exertion leads to increased cellular energy demands. In order to meet these energy requirements, cells produce more ATP via cellular respiration, resulting in increased cellular uptake of oxygen and production of carbon dioxide waste. Heightened levels of carbon dioxide in the blood activate chemoreceptors in the carotid artery and brain to increase sympathetic tone, ultimately leading to an increase in heart rate, stroke volume, cardiac output, and therefore arterial blood pressure. Additionally, decreased levels of oxygen … and compression-induced relaxation of smooth muscle cells lead to vasodilation of the vascular beds of working tissue. This increased cardiac output during exertion sustains the physical activity evident in both prints and contributes to the characteristically flushed skin-tone of exercising bodies as portrayed in *The Lovers* (India).
>
> [In Rembrandt's *Joseph and Potiphar's Wife*,] Joseph's expression is pained: you can see the wrinkles in his brow,

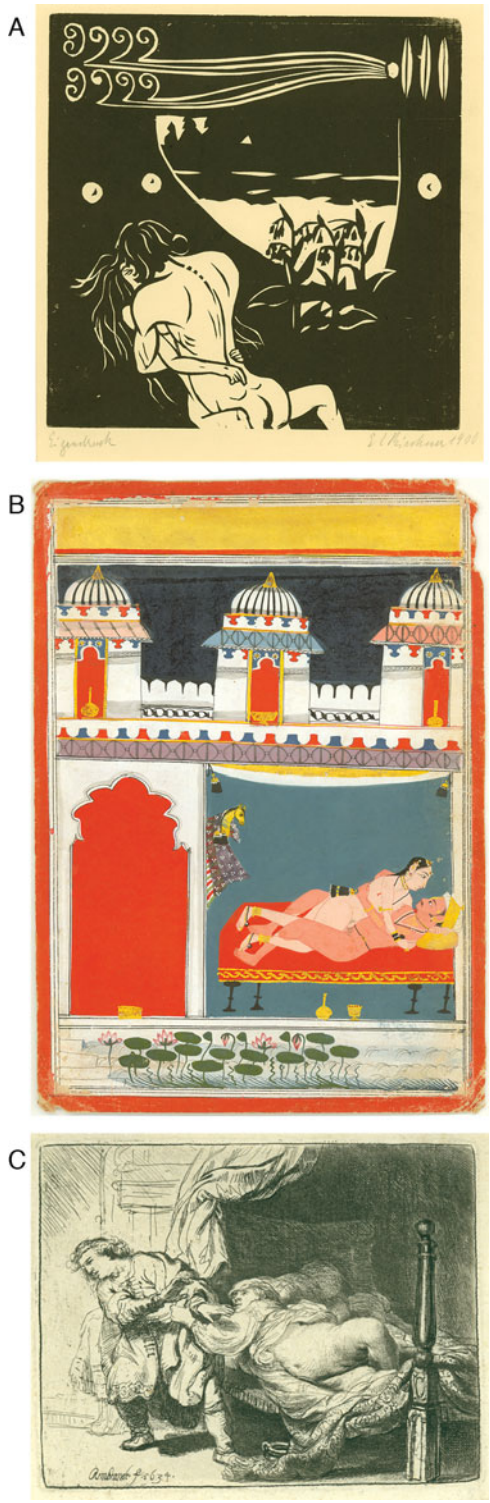

Figure 1. Examples of artworks used in the activity. (A) Ernst Ludwig Kirchner (German, 1880–1938), *Union*, from the series *Man and Wife*, 1900. Woodcut; image, 203 × 203 mm (8 × 8 in.); sheet, 414 × 299 mm (16 5/16 × 11¾ in.). AMAM, Mrs. F. F. Prentiss Fund, 1955.19. (B) Indian, *Lovers*, ca. 1650. Ink, opaque watercolor, gold shell; 216 × 152 mm (8½ × 6 in.). AMAM, gift of Paul F. Walter, 1976.34. (C) Rembrandt Harmensz van Rijn (Dutch, 1606–1669), *Joseph and Potiphar's Wife*, 1634. Etching; 92 × 114 mm (3 5/8 × 4 ½ in.). AMAM, gift of the Max Kade Foundation, 1968.126.

the despair in his eyes and the pained set of his jaw as he pulls away from Potiphar's wife. Joseph's face and body are facing away from Potiphar's wife, and his hands seem to be pushing her mostly-naked body away from his fully clothed body. She, in contrast to Joseph, is the paradigm of decadence. She is so obese that her legs seem out of proportion with the rest of her body. Additionally, her lower genitalia, though they should be exposed by her position, are obscured. Further decadence is acknowledged by the ornate detail on her bed post and sheets. With decadence comes want, so as expected, her countenance is longing for Joseph, and she is trying to clutch him to her. At this frozen moment of time, Joseph is standing in the light, being pulled by the literal dark side of the etching where Potiphar's wife is located. He is experiencing the typical fight-or-flight response as he tries to escape her desirous and lecherous grasp. Potiphar's wife, on the other hand, is experiencing addiction to Joseph, indicative of increased levels of dopamine that stimulate the reward pathway and create a sense of desperate need. Mrs. Potiphar is clearly obese, and this could have had significant effects on her health, most notably hypertensive effects potentially caused by the large amount of leptin secreted from the large number of adipose cells in her body. [Accompanying the students' composition were two flowcharts: one illustrating a path from decreased vagal tone and increased sympathetic tone to increased blood pressure; the other outlining a path from elevated levels of plasma leptin to increased blood volume and blood pressure via activation of the sympathetic nervous system.]

These extracts bear witness to the manner in which the project served as a capstone, one that helped students to integrate knowledge gained prior to the project.

Although broadening in scope over its various offerings, the art project retained at its core the three essential components (preparatory readings, visual analysis of artworks, and presentation of a mini-exhibition), as well as assessment focused on gains in analytical ability and on students' experience of the activity. The assessment strategy is summarized in Table 3 and elaborated subsequently. Students' participation in the assessments was voluntary. All students chose to participate, and only absence due to sickness kept students from participating.

Assessing Whether Gains in Analytic Ability Can Be Achieved through an Art-Based Activity of Limited Duration

Direct assessment of visual analytical skill was performed in the 2011 offerings of Animal Physiology and the first-year seminar. Students were given 10 min in class to examine and then write a visual analysis of an image unrelated to love prior to the art project and again at the end of the semester. Two images were used, with half of the students analyzing *In the Mountain* (Marc Chagall, 1930, oil on canvas) and the other half analyzing *La Solitudine* (Giorgio de Chirico, ca. 1915, oil on canvas) at the project's start. At the end of the semester, students analyzed the alternate painting. All analyses were scored after the end of the semester by an art historian (L.M.) blinded to which analyses were pre- or postproject and in which class (the advanced physiology course or the first-year seminar) each analysis was prepared. The scoring rubric (Table 4), with a maximum score of 21 points for an analysis attaining the highest benchmarks in the seven categories,

Table 3. Assessment overview

Query	Assessment based on quantitative, experimental-design approaches	Assessment based on qualitative approaches
Are analytical gains achievable?	Direct: paired analysis of pre- and postproject scores on visual analysis of a painting (Animal Physiology, 2011; seminar, 2011) Numerical survey: scores on postproject questionnaire on students' impressions (Animal Physiology, 2010–2012; seminar, 2011, 2012)	Content analysis of comments to open-ended prompt on postproject numerical survey (Animal Physiology, 2008–2011; seminar, 2011), as well as metacognitive reflections in end-of-semester portfolio (Animal Physiology, 2010, 2011)
How is the activity experienced by students?	Numerical survey: scores on postproject questionnaire on students' impressions (Animal Physiology, 2008–2012; seminar, 2011, 2012)	Content analysis of comments to open-ended prompts on postproject numerical survey (Animal Physiology, 2008–2011; seminar, 2011), as well as metacognitive reflections in end-of-semester portfolio (Animal Physiology, 2010, 2011)

Table 4. Scoring rubric for assessment of visual analysis

Visual element	3 points	2 points	1 point
Composition	Observes accurately the arrangement of figures/objects without missing any one; comments on the way they relate to each other; uses effective descriptive language	Observes and describes the general arrangement of objects/figures, focusing on the largest without noting detail	Makes general observations about the figures/objects in the scene without much description or commentary on their relationships
Space and setting	Describes accurately the space that the figures/objects occupy, including the use of perspective; finds the most appropriate words to describe it; identifies the setting and discusses the spatial division, i.e., mentions fore-, middle, and background of the work	Identifies the setting, makes general comments about the work's spatial characteristics; uses appropriate words; does not note the use of perspective or the spatial division of the pictorial field	Identifies the setting but does not account for any of the spatial characteristics; no attempt at finding accurate language
Scale and viewpoint	Describes accurately the scale and point of view (viewer's position vis-à-vis the image); finds the most appropriate words to use in the description; comments on any distortions	Exhibits awareness of the scale of figures/objects and the viewpoint and their importance, but mentions them in an indirect way	Shows some recognition of scale and viewpoint; refers to one or the other in vague terms
Colors	Observes keenly the use of colors and where they appear in the pictorial field; uses adjectives that precisely describe the colors; comments on the repetition of certain colors or their intensity/saturation; comments on any unnaturalistic use of color; possibly notes handling of paint	Recognizes and describes the colors with brief mention of some of the following: repetition, different shades, saturation, unnaturalistic use, paint handling	Mentions only the most prominent colors and what/where they describe; no mention of repetition, shades, etc.
Lines and shapes	Observes the use of (different kinds of) line (and outlines) and comments on the shapes in general (geometric, organic, etc.); comments on how shapes are constructed, whether through line or color (brushstroke, staining) and their overall effect	Comments on the type(s) of shapes in the work and the overall effect they produce; some recognition of lines and outlines	Basic description of shapes with little or no commentary on line
Light and light source	Notes the source (and direction) of illumination, including the play of light and dark it produces; comments on how lighting affects (shadows, light-dark contrast) the picture and whether it is (or is not) realistic	Comments on light source or overall quality of light; notes the effect that light is producing	Recognizes the general quality of light or mentions light in regard to a particular time of day
Main theme or event correctly identified, artist's choices analyzed, offering an interpretation	Identifies correctly what is happening in the image (or points out the absence of any action); analyzes the meaning that all visual components advance together as a whole and offers personal interpretation/take on the scene	Identifies the scene, but in vague terms, and offers an interpretation only loosely based on the visual evidence without much justification for said interpretation	Only partially (or not at all) identifies the scene and with only a rudimentary interpretation (or none)

Table 5. Numerical survey of students' impressions, based on a 5-point Likert scale (1 signifying "very little" and 5 signifying "very much")

	Question	Respondents	Median	Mode
1.	To what extent did the project pique your curiosity?	144	4	4
2.	To what extent was working with original art pieces engaging?	142	4	5
3.	To what extent was learning about ways in which culture influences perceptions of depression engaging?	80	4	5
4.	To what extent was learning about the biology of love engaging?	81	5	5
5.	To what extent was learning how an art historian approaches visual analysis engaging?	81	4	4
6.	To what extent were crafting and presenting a four-piece art exhibit engaging?	81	4	4
7.	In comparison with textbook descriptions, was the perspective on the body offered by the art pieces valuable or meaningful?	143	4	4
8.	Having done the project, do you feel more knowledgeable of the symptoms of depression and bodily ways in which it is manifested?	112	3	4
9.	Having done the project, do you feel more knowledgeable of bodily ways in which the emotion of love is manifested?	100	4	4
10.	To what extent did the project prompt you to synthesize (i.e., make connections), especially between the autonomic nervous system and other parts of the body?	145	4	4
11.	To what extent did the project prompt development of observational skills (i.e., visual acuity)?	81	4	4
12.	To what extent did the project create an opportunity for you to examine and discuss your understanding of concepts?	32	4	4
13.	To what extent did the project promote interaction, cooperation, and collaboration between and among students?	32	4.5	5

was based directly on outcomes and performance criteria pertaining to visual literacy standards for higher education formulated and adopted by the Association of College and Research Libraries (2011). The outcomes specify, for example, that visually literate college students can: 1) identify the subject of an image; 2) explore choices made in the image's production (e.g., composition, staging); and 3) describe pictorial, graphic, and aesthetic elements of an image (e.g., color, contrast). The validity and reliability of the instrument were not evaluated as part of this project.

Complementing data from the direct assessment of visual analytical skill were two other bodies of information. One comprised scores on a 5-point Likert scale given to questions on a survey of students' impressions; the survey was administered at the end of the semester, generally 1 wk after the conclusion of the art project. The numerical survey is provided in Table 5; a subset of the questions was used for each course, with the selection of questions varying. Survey question 11 probes students' views on the extent to which the project nurtured development of visual analytical skills.

Also providing complementary data were comments to an open-ended prompt at the end of the survey, as well as metacognitive reflections given in portfolios submitted by Animal Physiology students at the end of the semester. Sixty-one of the 133 surveys completed between 2008 and 2011 offered comments on the project, and 22 of the 52 portfolios submitted in 2010 and 2011 included metacognitive reflections on the art project. Presentation of a portfolio was compulsory, but students were allowed full freedom in their choice of any four class activities and assignments on which to reflect metacognitively. The comments and reflections were analyzed for emergent themes by using the methodology of conventional qualitative content analysis (reviewed by Hsieh and Shannon, 2005). Comments and reflections were independently analyzed for emergent themes and code words by one of the authors (T.A.) and by Oberlin's Director of Sponsored Programs (P. Snyder), who has undergraduate and graduate training in literary analysis. Then, comments and reflections were independently mapped to the emergent themes by two of the authors (L.M. and T.A.) and by P. Snyder. If all three mappers mapped a comment or reflection to the same theme, then the correlation was accepted. Note that a comment or reflection could map to multiple themes.

Assessing Whether Students Experience the Activity as Engaging, Meaningful, and Thought-Provoking

Data from the qualitative content analysis, as well as the numerical surveys, also addressed the second question of the experiment, namely, how students experienced the project. Qualitative content analysis is an ideal approach for addressing this question, because it elucidates the emergent meanings of individuals' experiences, as well as patterns and themes within these experiences. (See, e.g., Hein, 1998, especially pp. 54–77, which usefully contrasts the merits of the qualitative or naturalistic paradigm with those of the quantitative or experimental-design paradigm; Tishman *et al.*, 2007, especially pp. 9–10, also contrasts the merits and highlights the distinctive suitability of qualitative analysis for capturing the quality of subjective experiences in higher cognition.) Thus, qualitative analysis illuminated students' internal experience and process of higher cognitive skill development, whereas quantitative analysis defined the extent to which skills developed. Additional information came from the numerical surveys. Survey questions 1–6 probed whether the project intellectually engaged students. Questions 7–10 examined whether students found the project meaningful, especially with respect to broadening ways to engage with the course material. Questions 10 and 11 concerned whether students perceived development of critical-thinking skills related to synthesis and analysis. Questions 12 and 13 sought to assess the extent to which the project created opportunities for students to collaborate on the construction of understanding.

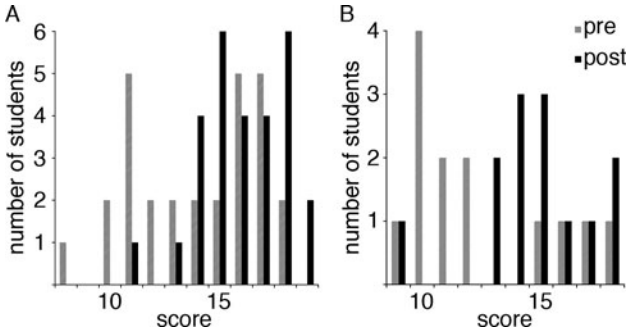

Figure 2. Histogram of scores on visual analyses performed before (gray) and after (black) the art project by 28 students in Animal Physiology (A) and 13 in the first-year seminar (B). The maximal possible score was 21. Absence from class due to illness prevented completion of the assessment by four students in Animal Physiology and two in the first-year seminar; their data were excluded from analysis because they were incomplete.

RESULTS

Question 1: Can Gains in Analytical Ability Be Achieved through an Art-Based Activity of Limited Duration?

This question was addressed in part through direct assessment of students' visual analytical skill in the 2011 offerings of Animal Physiology and Body in Health and Disease. For the assessment, students visually analyzed an image of an artwork unrelated to love prior to and following the art project. A crossover design was used. For the preproject test, half of the students analyzed *In the Mountain* (Marc Chagall, 1930, oil on canvas), and the other half examined *La Solitudine* (Giorgio de Chirico, ca. 1915, oil on canvas). The analyses were marked against a rubric with a 21-point scale (Table 4), and the resulting data showed that, in both the upper-level physiology course (Figure 2A) and the first-year seminar (Figure 2B), students advanced in their ability to analyze visually. Twenty-eight of the 32 students in the physiology course completed both the pre- and postproject assessments. Four students missed either the pre- or postproject assessment due to illness; their data were incomplete and were excluded from the analysis. On the 21-point scoring scale, the median paired gain from pre- to postproject scores for the 28 students who completed the assessment in Animal Physiology was 2, and the null hypothesis of no gain was rejected ($p = 0.0014$ for directional Wilcoxon signed-rank test, with $W = 222$, $n_{s/r} = 25$). Thirteen of the 15 first-year seminar students completed both the pre- and postproject assessment. Two students missed either the pre- or postproject assessments due to illness, and their data were excluded from analysis because they were incomplete. For the 13 students who completed both the pre- and postproject assessment in the first-year seminar, the median gain was 3, and the null hypothesis was rejected ($p = 0.0102$ for directional Wilcoxon signed-rank test, with $W = 67$, $n_{s/r} = 13$). Pooling the results from the two courses yielded a median gain of 2, also statistically significant ($p = 0.0001$ for directional Wilcoxon signed-rank test, with $W = 521$, $n_{s/r} = 38$).

That students advanced in analytical ability was supported by students' responses to a postproject numerical survey administered in six offerings of Animal Physiology and two offerings of the seminar (Table 5). In particular, the median and mode for survey question 11 (students' impression of the extent to which the project prompted development of observational skills) were 4 on a 5-point Likert scale (1 signifying "very little" and 5 signifying "very much").

Additional data bearing on question 1 emerged from conventional content analysis of metacognitive reflections given in the end-of-semester portfolios of students in the 2010 and 2011 offerings of Animal Physiology. Metacognitive reflections were submitted for analysis in only these two offerings of the course. Students were prompted to reflect on any four course activities, assignments, or projects of their choosing, and 22 of the 52 students opted to comment on the art project. Examination of the reflections related to the art project revealed analysis and synthesis as the most prominent theme (Table 6), with 15 reflections from a total of 22 (i.e., 68% of those reflections mentioning the art project) highlighting this theme. The qualitative content analysis, along with the numerical survey of students' impressions, not only supported that gains in analytical ability can be achieved through participation in the project, but also offered much information on the undergraduates' experience of the project, as elaborated subsequently.

Question 2: Do Students in Biology Courses Experience the Art-Based Activity as Engaging, Meaningful, and Thought-Provoking?

Survey questions 1–6 (Table 5) probed whether various facets of the project engaged students intellectually, and for these six questions the median and mode equaled or exceeded 4 on the 5-point scale. With one exception, the median and mode were 4 for responses to questions 7–10, which examined whether students found the project meaningful, especially with respect to broadening ways to engage with the physiology course material. The exception was question 8, which concerned familiarity with the symptoms of depression and had a median of 3 and mode of 4. While depression was the concern of some preparatory readings (e.g., Ots, 1990), the project as a whole was centered on love. With regard to whether students perceived development of critical-thinking skills related to synthesis and analysis (questions 10 and 11), both median and mode were 4. The median and mode equaled or exceeded 4 for questions 12 and 13, which addressed the extent to which the project created opportunities for students to collaborate on the construction of understanding.

That the project piqued undergraduates' curiosity and provoked thought was further supported by content analysis of comments logged on the survey of impressions that was administered to students in the six assessed offerings of Animal Physiology and both offerings of the seminar (Table 7). The most prominent theme emerging from the comments was the intellectual stimulation engendered by the project: 32 (52%) of the 61 surveys offering comments from a total of 133 surveys completed between 2008 and 2011 described the project in such terms as *refreshing*, *engaging*, *creative*, and *enjoyable*. Other themes emerged as well, although in appreciably fewer comments. For example, each of the following themes was represented in ~15% of the surveys with comments: the project bridged art and science, was helpful, and was challenging. Seven of the 61 surveys with comments (11%) suggested that the project was unsatisfying: four of these indicated that

Table 6. Student reflections on the art project from metacognitive journals: coded themes and representative quotes

Theme, code words	% including theme in response	Representative quotes
Theme 1: The project involved analysis and synthesis (breaking a problem down into parts and then synthesizing an answer).		
break into parts, analyze, put back together, synthesize, evaluate	68	"The synthesis of the information you gathered from your observations then happens partly on the spot, while you're hot in discussion with your lab partners; whereas a huge chunk of it also happens when you're at home and trying to write the essay, while you're deep in thoughts trying to understand and make sense of the details of the painting. Finally, writing up the essay is when you evaluate the strength[s] and weaknesses of your synthesis, and try to piece all the information together to form a general idea/theme on the picture. To me, finishing an essay through such a process is a very rewarding process, which was something I have never done before, especially not in Biology class."
Theme 2: The project nurtured students' ability to convey and defend ideas.		
words, communicate, express, discuss, describe, defend, speculate, discussion, justify, explain, critique, support, make claims	36	"This assignment also forced me to develop a hypothesis from a rather abstract concept, and strongly defend this idea with evidence found within the paintings."
Theme 3: The project prompted students to observe carefully (before jumping to interpretation), leading to new or deeper insights.		
observe, study, scrutinize, observation, look deeply	36	"I think that the museum project did a really great job teaching us to *first* find clues and *then* start to defend your reasoning . . . I think my tendency was to jump straight to conclusions when I looked at a piece of art, perhaps taking a small visual piece of the art with me to defend myself. But by listing what I could see, I was able to start putting the pieces together more effectively."
Theme 4: The project prompted the making of connections.		
a. our, we, together, group	36	"Working in a group has also been enlightening, as synergistic thoughts can emerge from discussion of perplexing problems."
b. bridging, linking, interconnecting, integrate, link	23	"Through integrating art with science, I can apply what I know about both of those things to better my understanding of the other. I can look at science creatively and art analytically."
Theme 5: The project was valuable and relevant.		
apply, application, real-life, relevant, relative, valuable, rewarding	32	"At the beginning of the semester, when I first heard that we were going to be doing some of our labs in the art museum, I was confused. I had difficulty understanding how looking at works of art could enhance my knowledge of physiology. After the first lab period, I found my ideas about physiology expanding. I began to realize that physiological concepts could be applied to almost anything in life that deals with the human body. For me, it was a huge breakthrough in my thinking to finally be able to use the ideas that I had learned in a science class to better the world around me."
Theme 6: The project interested students.		
enjoy, amazing, inspire, captivating	27	"Working together to develop a concept of what was happening, both emotionally and physiologically, in the prints led to one of the more interesting and exciting projects of the semester."
Theme 7: The project was hard.		
frustrating, challenging, uncertainty, had trouble	23	"Something that most frustrated me (and later inspired me) in this class was the level of subjectivity that we would sometimes encounter. More specifically, I'm referring to the visual analysis and the art museum visits we would take."
Theme 8: The project called for creativity.		
creativity, creative, new, construct	14	"Not only did this project require higher thinking skills but also artistic creativity."

respondents felt adrift in the assignment; four referred to the project's offering nothing useful; and two to unpleasantness (e.g., having to stand during the museum visits).

While the comments provided on the survey highlighted the intellectual stimulation afforded by the project, metacognitive reflections focused on the thinking and reasoning prompted by the project (Table 6). These reflections came from the end-of-semester portfolios of 22 of the 52 students who enrolled in the 2010 and 2011 offerings of Animal Physiology and who were required to submit a portfolio containing metacognitive reflections on any four class assignments, projects, or activities of their choosing. As noted previously in this section, the project's prompting of analysis and synthesis was the most prominent theme, expressed in 68% of the

Table 7. Coded themes and representative quotes from students' comments on survey[a]

Theme, code words	% including theme in response	Representative quotes
Theme 1: The project was intellectually stimulating.		
a. interesting, engaging, stimulating, original, welcome, new, refreshing, creative, fun, enjoyable, longing for more	52	"I thought this project was a very interesting, creative way of learning material."
b. made me think in a new, different way	7	"Very unique project! Got me thinking in new ways about old things."
Theme 2: The project bridged art and science.		
connections, interdisciplinary, cross-disciplinary, bridge, intertwined	15	"I found the project somewhat 'unsettling' only in the sense that it asked me to engage with a totally unfamiliar discipline—in retrospect, I think it's really valuable to give students the opportunity to forge cross-disciplinary connections, especially in the natural sciences, which tend to remain somewhat insular."
Theme 3: The project was helpful.		
helpful, valuable, helped	13	"It wasn't scientifically helpful, but it was in a creative way, and I will remember that stuff forever now. It really got me thinking,"
Theme 4: The project was challenging.		
a. background, example	13	"I think it was hard to grasp exactly what we were supposed to be doing. But then you gave us the example of Nan Goldin's photograph and told us your physiological interpretations. That made the project much more clear."
b. hard, tough	11	"Going to the art museum was fun and engaging, but attempting to connect paintings with hard neuroscience is a difficult task. It's hard to write a group essay."
Theme 5: The project conveyed relevance of course concepts.		
relevant, contextualized, application, embodied, integrating with reality	10	"Very helpful in integrating lectures w/ reality. I've never looked at art that way before." "By putting them [bodily manifestations] in a real context where we were able to examine them and dissect them. It allowed for better understanding and retention of the material."
Theme 6: The project prompted higher-level thought.		
analyze, analysis, synthesize, think, interpretation	8	"It was fun to try [to] analyze physiology based on prints, and it's something I've never done before. I love looking at prints and trying to see beyond the picture. It forced you to analyze them without any real support (you must decide what is happening on your own)."
Theme 7: The project was unsatisfying.		
a. project left student uncertain, adrift, grasping at straws, making things up	7	"I just felt like I was looking at the art and grasping at straws to draw conclusions about physiology. I think if more realistic art had been used (i.e. where you could see sweating or a reddening of people's faces) it might have been a more valuable project. Overall, I felt like it did not aid in my understanding of physiology."
b. project offered nothing useful	7	"I didn't think the exercise of art observation was all that related to physiology—doing this project required some stretches to force physiological explanation/interpretation onto art pieces."
c. project was unpleasant (group work, standing)	2	"Museum is a tiring (standing) context for learning."

[a]Sixty-one surveys offered comments from a total of 133 surveys completed between 2008 and 2011.

art-project reflections. Other common themes, represented in 32–36% of the reflections, included that the project called for discussion of ideas, required careful observation, encouraged the making of connections, and brought physiological concepts to life in a way that conveyed their relevance. Thus, data from qualitative content analysis of the metacognitive reflections, as well as the comments logged on the surveys, aligned with quantitative results from the direct assessment of visual analytical skill and numerical survey of students' impressions, indicating that the project engaged students and nurtured deep thinking.

DISCUSSION

Asking students to examine art through the lens of biology, the project was formulated with the goals of piquing students' curiosity, broadening the ways in which undergraduates meaningfully engage with the physiology course material, and developing higher-level thinking skills. Whether these goals were met was evaluated via a strategy involving quantitative and qualitative analyses.

Stimulation of students' curiosity was well-evidenced by the data: the mode and the median of responses to the six

survey questions related to curiosity and engagement (questions 1–6) were either 4 or 5, with 5 the highest score on the Likert scale. From delving into visual analysis and the topic of love to working with original pieces of art and crafting one's own mini-exhibition, the individual components of the art project captured the students' interest, thereby helping students to bridge biology and art. Also enabling this bridge to be made was the guidance on visual analysis given at the start of the project (see Table 7, theme 4, category a). This guidance gave direction to the students in the novel task of examining art in a science class and, moreover, prompted students to plumb the complexity of the artworks, which had been chosen for their ability to captivate and to be open to multiple interpretations. Thus, in intellectually engaging the students, the components of the project and the guidance provided at the project's start lessened any reticence on the part of students to analyze art through the lens of biology.

Additionally, the components of the project collectively offered a fresh, different way in which to contemplate the physiological content of the courses. The intellectual stimulation afforded by the project was the most prominent theme in students' comments (Table 7, theme 1), and the words used by students when describing the project (e.g., *refreshing* and *welcome*) are reminiscent of those associated with the experience of flow in a creative endeavor (e.g., Csikszentmihalyi, 1996). The experience of flow, closely connected to enjoyment, arises when tackling a difficult creative problem in which one's skills and the problem's challenges are both high and balanced (Csikszentmihalyi, 1996). Intriguingly, whether talented in the sciences or in the arts, students are more likely to experience flow in the arts than in the sciences, and associated with this positive experiential state are heightened positive affect, self-esteem, and intrinsic motivation (Csikszentmihalyi and Schiefele, 1992). Thus, in engendering a creative experience, the project offers a strategy for nurturing science students' creativity, complementing approaches such as peer instruction, which promote associative thinking (for review, see DeHaan, 2011).

Similar to the way it intellectually engaged students, the art project afforded valuable, meaningful perspectives on the body in comparison with those given in textbooks, and it prompted synthesis among topics within the course and between biology and other disciplines. These conclusions are borne out in the survey (questions 7 and 10, both of which had median and mode of 4), as well as the themes that emerged from students' metacognitive reflections (Table 6, especially themes 1, 4, and 5) and comments (Table 7, especially themes 2, 3, 5, and 6). Additionally, while achieving these ends, the project also altered the classroom dynamic by bringing different student voices to the fore. Conceivably, the project elicited the participation of students whose learning styles were better served by the visual analysis inherent in the activity than by the quantitative reasoning characteristic of most class discussions throughout the courses.

The art project also was designed to develop higher-level thinking skills in multiple ways. In asking students to generate analyses and interpretations and then to articulate these, the activity encouraged the undergraduates to think independently and to use and articulate evidentiary reasoning. By having undergraduates work in groups to interpret the artworks and to craft a mini-exhibition, the project created the opportunity for students to adopt a critical orientation as they impartially examined evidence supporting each group member's interpretations. Moreover, through this group work, the activity prompted development of intellectual maturity, as students negotiated among multiple interpretations.

That the project succeeded in calling on higher-level thought and developing skills inherent in such thought is supported by assessment data and metacognitive reflections in the portfolios of students in Animal Physiology (Tables 5 and 6, respectively). In addition, direct assessment of visual analytical skill revealed a statistically significant gain in skill correlating with participation in the art project (Figure 2). The absence of a control group, members of which would have taken the visual assessment but not participated in the project, limits arguments about causality; however, complementing the correlative finding were students' answers to two survey questions related to analysis and synthesis (questions 10 and 11, with median and mode of 4 for both questions on the 5-point scale). Content analyses of the undergraduates' metacognitive reflections (Table 6) and comments (Table 7) likewise bear witness to the exercise of higher-level thought engendered by the art project. Thus, in asking students to articulate and negotiate among reasoned analyses, particularly within the realm of uncertainty afforded by artworks, the activity nurtured characteristics of an inquiring mind.

The success of the art activity hinged, from the instructor's vantage, on three components, each of which harkens back to the development of higher-level thinking skills noted in the previous paragraph. First was the inclusion of solid guidance on what was expected analytically: at the start of the project, students were led through a visual and physiological analysis of one artwork. The second key component was presentation of a mini-exhibition addressing a thematic question. The written and oral presentations of these exhibitions forced students to make their thinking explicit and coherent, and, as has been argued in the case of writing (Hacker *et al.*, 2009), making thinking explicit is a valuable metacognitive activity in its own right. The third component contributing to the activity's success was the group work, for this required students to examine critically the persuasiveness of each group member's reasoning as well as negotiate among competing interpretations. By having students collaborate to make sense of the artwork, the second and third components made the art activity both knowledge and community centered, two characteristics associated with effective learning environments (reviewed in National Research Council, 2000).

A worthwhile question is whether the art project critically depends on the use of original artworks in a museum setting. The project can, indeed, be done with reproductions viewed in a usual classroom. For example, in the 2007 offering of introductory biology at Oberlin, the museum curator visited the 143-student class and projected images of four artworks onto the screen in the lecture hall; in small groups, students then analyzed and discussed the artworks. Yet, much is to be gained by engaging students with art in a museum. In particular, the authenticity of original artworks invites careful observation: between the observer and the artwork, deep connections and complex interactions occur, and from a constructivist vantage, these lie at the heart of learning (Tishman *et al.*, 2007). Bearing out the intellectual engagement inherent in these connections and interactions are both

quantitative data (Table 5, question 2) and qualitative data (Table 6, theme 6, and Table 7, theme 1). Complementing the value of using original artworks is the role that museums have in helping observers to make connections with the artworks. Both creating expectations and setting tone, the museum environment signals to students that they are entering "a kind of sanctuary, special and set apart," one that promotes deep engagement (Tishman *et al.*, 2007, p. 17). Entering this deep engagement is facilitated by the curators, who are particularly adept at encouraging close observation and sense-making, as well as facilitating conversations that nurture learning.

In engaging science students with original artworks, the art activity bears some similarity to previously described curricular endeavors bridging art and science. Many of these are elective courses of 10–30 h of contact time situated in medical schools and seek to develop observational skills (Bardes *et al.*, 2001; Dolev *et al.*, 2001; Elder *et al.*, 2006; Shapiro *et al.*, 2006; Naghshineh *et al.*, 2008; McLean, 2009), as well as evidentiary reasoning and teamwork (Reilly *et al.*, 2005). While most of these courses center activities on close examination and interpretation, one seeks to develop observational skills by having medical students examine art and draw (McLean, 2009). The emphasis on drawing to prompt keen observation echoes the approach of Louis Agassiz and exemplifies one long-standing constructivist approach to learning (Lerner, 2007). Observational skills are also stressed in a curricular project in which life sciences undergraduates examine not only the ecological plausibility of artworks (e.g., of Henri Rousseau's *The Equatorial Jungle*) but also the artistic form of ecological models (Kangas, 1998). As with the art project on love, the ecological art activity emphasizes visual analysis. A different emphasis, one on "learning communities" composed of undergraduates from various disciplines, is made in another curricular endeavor melding art and science. In this activity, students studying art, biology, computer science, and nursing form teams to conduct anatomical research, for example, imaging zebrafish brain (Needle *et al.*, 2007). This activity shares with the art project on love a reliance on group work to nurture intellectual maturity.

These endeavors bridging art and science are founded on the belief that the critical-thinking skills promoted through art-based activities are transferable to science. Supporting this belief is the 5-yr longitudinal study of Housen (2001–2002), which demonstrated through a controlled experimental design that transfer occurs both across subject domain and across social context (e.g., whether the student is working alone or collaborating with others). Moreover, with respect to visual analytical skill, evidence of its transferability from a museum context to a life sciences setting comes from three experimental-design studies (Kirklin *et al.*, 2007; Pellico *et al.*, 2009; Klugman *et al.*, 2011). For example, in an accelerated master's degree program in nursing, those students participating in art-based visual training performed better than those receiving conventional training on two measures of observational skill: the number of observations and objective clinical findings drawn from analysis of patient photographs; and the number of alternative diagnoses based on the observations (Pellico *et al.*, 2009). Testing whether the enhanced visual analytical skills documented by Pellico *et al.* (2009), as well as by the present work, lead to gains in students' ability to make sense of scientific graphs and structural data (e.g., crystallographic structures) would be a valuable extension of the present report.

Given the data in support of transfer, the art activity was designed to incorporate conditions believed to promote transfer of knowledge. While multiple mechanisms of transfer likely exist (e.g., Nokes, 2009), transfer itself can usefully be divided into two forms: a so-called low-road transfer involving practice to the point at which a skill is used automatically when cued, and a so-called high-road transfer, dependent upon mindful abstraction (i.e., generalization) of a skill from the context in which learned, allowing its deliberate use in another context (Salomon and Perkins, 1989). The art project's duration was insufficient to support the extensive practice underlying low-road transfer. Instead, the project promoted mindfulness and abstraction, two essential components of high-road transfer (Salomon and Perkins, 1989). Mindfulness was engendered, for example, by the curiosity provoked by the art, as well as by the group-based exploration of alternative interpretations arising from the ambiguity inherent in artworks (for elaboration on mindfulness, see Langer, 1989, 1993). Abstraction was prompted by the metacognition involved when students were asked to make their thinking explicit (Hacker *et al.*, 2009). That mindfulness and abstraction did indeed occur was borne out by the qualitative analyses of students' comments and reflections (see Table 6, themes 1, 2, and 3, as well as Table 7, theme 1). Importantly, the mindfulness engendered by the art project can be expected to help not only during the project itself, but also at the point when skills and knowledge are deliberately brought to bear in a new situation (Langer and Piper, 1987), as is needed for transfer to be complete (Salomon and Globerson, 1987).

At first glance, developing skills in art for transfer to a domain such as science may seem circuitous, but characteristics of art make it ideal for development of critical thinking, especially through approaches formulated in the Artful Thinking Program of Project Zero (Tishman and Palmer, 2006). As highlighted by Housen (2001–2002), well-chosen artwork can simultaneously be accessible, compelling, provocative, and ambiguous, all of which promote mindfulness. Ambiguity invites multiple interpretations, as well as evidentiary reasoning for these interpretations. The accessible, compelling, provocative nature of art piques curiosity and elicits engagement, both of which are key in approaches drawing on constructivist theory (Dewey, 1913; Julyan and Duckworth, 1996). Moreover, use of emotional images in learning activities enhances memory for the associated content information (Berry *et al.*, 2008). These attributes of art were tapped in the present activity through examination of a selection of artworks relating to the theme of love through the disciplinary frame of biology. In keeping with constructivist theory and student-centered, active-learning approaches, students' curiosity was piqued, their ways of meaningfully engaging with course material broadened, and their critical-thinking skills nurtured. These characteristics of the project also align well with the desires of students in the sciences and with recommendations for stemming the loss of talented science students to non-science majors (Seymour and Hewitt, 1997; AAAS, 2011). More broadly, with outcomes aligning with the recommendations of *Vision and Change in Undergraduate Biology Education: A Call to Action* (AAAS, 2011), the project thus contributes to the pool of strategies for nurturing the intellectual growth of biology students.

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REFERENCES

American Association for the Advancement of Science (2011). Vision and Change in Undergraduate Biology Education: A Call to Action, Washington, DC.

Anderson A, Middleton L (2006). What is this thing called love? New Sci *190*, 32–34.

Association of College and Research Libraries (2011). ACRL Visual Literacy Competency Standards for Higher Education. www.ala.org/acrl/standards/visualliteracy (working draft was accessed 11 July 2011).

Bardes CL, Gillers D, Herman AE (2001). Learning to look: developing clinical observational skills at an art museum. Med Educ *35*, 1157–1161.

Barnet S (2008). A Short Guide to Writing about Art, Upper Saddle River, NJ: Pearson.

Berry C, Schmied LA, Schrock JC (2008). The role of emotion in teaching and learning history: a scholarship of teaching exploration. Hist Teach *41*, 437–452.

Brown P (2003). In the shadow of fear. New Sci *179*, 30–35.

Cannon WB (1928). The mechanism of emotional disturbance of bodily functions. N Engl J Med *198*, 877–884.

Cannon WB (1934). The significance of the emotional level. Sci Mon *38*, 101–110.

Csikszentmihalyi M (1996). Creativity, New York: Harper Collins.

Csikszentmihalyi M, Schiefele U (1992). Arts education, human development, and the quality of experience. In: The Arts, Education, and Aesthetic Knowing, ed. B Reimer and RA Smith, Chicago: National Society for the Study of Education, 169–191.

DeHaan RL (2011). Teaching creative science thinking. Science *334*, 1499–1500.

Dewey J (1913). Interest and Effort in Education, Boston: Houghton Mifflin.

Dolev JC, Friedlaender LK, Braverman IM (2001). Use of fine art to enhance visual diagnostic skills. J Am Med Assoc *286*, 1020–1021.

Elder N, Tobias B, Lucero-Criswell A, Goldenhar L (2006). The art of observation: impact of a family medicine and art museum partnership on student education. Fam Med *38*, 393–398.

Fisher H (1998). Lust, attraction, and attachment in mammalian reproduction. Hum Nat *9*, 23–52.

Fox CA, Fox B (1969). Blood pressure and respiratory patterns during human coitus. J Reprod Fertil *19*, 405–415.

Hacker DJ, Keener MC, Kircher JC (2009). Writing is applied metacognition. In: Handbook of Metacognition in Education, ed. DJ Hacker, J Dunlosky, and AC Graesser, New York: Routledge, 154–172.

Hatfield E, Sprecher S (1986). Measuring passionate love in intimate relationships. J Adolesc *9*, 383–410.

Hein G (1998). Learning in the Museum, London: Routledge.

Housen AC (2001–2002). Aesthetic thought, critical thinking and transfer. Arts Learn Res J *18*, 99–131.

Hsieh H-F, Shannon SE (2005). Three approaches to qualitative content analysis. Qual Health Res *15*, 1277–1288.

Julyan C, Duckworth E (1996). A constructivist perspective on teaching and learning science. In: Constructivism: Theory, Perspectives, and Practice, ed. CT Fosnot, New York: Teachers College Press, 55–72.

Kangas P (1998). Art and the ecosystem. Am Biol Teach *60*, 20–26.

Kirklin D, Duncan J, McBride S, Hunt S, Griffin M (2007). A cluster design controlled trial of arts-based observational skills training in primary care. Med Educ *41*, 395–401.

Kleinman A (1977). Depression, somatization and the "new cross-cultural psychiatry." Soc Sci Med *11*, 3–10.

Kleinman A (2004). Culture and depression. N Engl J Med *351*, 951–953.

Klugman CM, Peel J, Beckmann-Mendez D (2011). Art rounds: teaching interprofessional students visual thinking strategies at one school. Acad Med *86*, 1266–1271.

Langer EJ (1989). Mindfulness, Reading, MA: Addison-Wesley, 61–79, 115–131.

Langer EJ (1993). A mindful education. Educ Psychol *28*, 43–50.

Langer EJ, Piper AI (1987). The prevention of mindlessness. J Pers Soc Psychol *53*, 280–287.

Lerner N (2007). Drawing to learn science: legacies of Agassiz. J Tech Writ Commun *37*, 379–394.

Levin RJ (2003). A journey through two lumens. Int J Impot Res *15*, 2–9.

McLean C (2009). Art enhances medicine. UW Medicine *32*, 22–23.

Naghshineh S, Hafler JP, Miller AR, Blanco MA, Lipsitz SR, Dubroff RP, Khoshbin S, Katz JT (2008). Formal art observation training improves medical students' visual diagnostic skills. J Gen Intern Med *23*, 991–997.

National Research Council (2000). In: How People Learn: Brain, Mind, Experience, and School expanded ed., ed. JD Bransford, AL Brown, and RR Cocking, Washington, DC: National Academies Press, 144–147.

Needle A, Corbo C, Wong D, Greenfeder G, Raths L, Fulop Z (2007). Combining art and science in "arts and sciences" education. Coll Teach *55*, 114–119.

Nokes TJ (2009). Mechanisms of knowledge transfer. Think Reason *15*, 1–36.

Ots T (1990). The angry liver, the anxious heart and the melancholy spleen. Cult Med Psychiatry *14*, 21–58.

Pellico LH, Friedlaender L, Fennie KP (2009). Looking is not seeing: using art to improve observational skills. J Nurs Educ *48*, 648–653.

Perry M, Maffulli N, Willson S, Morrissey D (2011). The effectiveness of arts-based interventions in medical education: a literature review. Med Educ *45*, 141–148.

Reilly JM, Ring J, Duke L (2005). Visual thinking strategies: a new role for art in medical education. Fam Med *37*, 250–252.

Salomon G, Globerson T (1987). Skill may not be enough: the role of mindfulness in learning and transfer. Int J Educ Res *11*, 623–637.

Salomon G, Perkins DN (1989). Rocky roads to transfer: rethinking mechanisms of a neglected phenomenon. Educ Psychol *24*, 113–142.

Seymour E, Hewitt NM (1997). Talking about Leaving, Boulder, CO: Westview.

Shapiro J, Rucker L, Beck J (2006). Training the clinical eye and mind: using the arts to develop medical students' observational and pattern recognition skills. Med Educ *40*, 263–268.

Szalavitz M (2002). Love is the drug. New Sci *176*, 38–40.

Tennov D (1979). Love and limerence, New York: Stein and Day.

Tishman S, McKinney A, Straughn C (2007). Study Center Learning: An Investigation of the Educational Power and Potential of the Harvard Art Museum's Study Centers. www.old-pz.gse.harvard.edu/Research/HAMPZStudyCenterLearning.pdf (accessed 1 March 2013).

Tishman S, Palmer P (2006). Artful Thinking: Stronger Thinking and Learning through the Power of Art. www.old-pz.gse.harvard.edu/Research/ArtfulThinkingFinalReport.pdf (accessed 20 September 2012).

Zeki S (2007). The neurobiology of love. FEBS Lett *581*, 2575–2579.