A conceptual overview of the role of beauty and aesthetics in science

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Abstract

After establishing an argument for attention to the role of beauty and aesthetics in science and scientific inquiry, this paper reviews literature in four areas that contributes to an understanding of a "scientific-aesthetic" space: (1) beauty in ideas and their form; (2) beauty in wonder, awe, and sublime; (3) beauty as it relates to cosmology and understanding God's design, and; (4) beauty in experience with science and scientific ideas. Following this, research exploring connections between aesthetics and science, including related conversations like interest, out-of-school transfer, and awareness building efforts, is discussed. The paper concludes with research exploring psychological and pedagogical analyses linking aesthetic experiences and science learning.

Introduction

To some it may seem odd to pair the arts with science. Much has been written on the fundamental differences between the two as well as the cultures in which they are practiced. Snow's The two cultures and the scientific revolution (1959), provides a detailed account of perceived fundamental differences between science and the social sciences (in which he includes the arts) in epistemology, ontology, and cultural values and norms of practice. Recently, however, we have seen a resurgence of attempts to connect the arts and sciences. To name just a few: Root-Bernstein (1997) has argued that science and art share a common underlying aesthetic motive and aesthetic theory; Holton (1973) argues for the role of imagination and artistic creativity in science; Chandrasekhar (1987), suggests scientists find motivation and desire to participate in science through aesthetics; McAllister (1996) appeals to aesthetics as a critical factor in a highly rational account of scientific progress and revolution; while Fischer (1999) seeks to blur the boundaries between science and art almost completely. We can also find calls to wed science and art in the writing of John Dewey and recent philosophers, aestheticians, and theorists who draw from Dewey's (1934/1980) theories and ideas (Fesmire, 1995; Garrison, 1995; Greene, 1981, 1995; Jackson, 1995, 1998; Prawat, 1993; Shusterman, 1992). The idea of a connection between art and science is not new. More importantly, conversations on the connection of art, beauty, and the aesthetic experience in science are gaining a voice in the science education community (Cavanaugh, 2005; Girod, Rau, & Schepige, 2003; Girod & Wong, 2002; Pugh, 2002, 2004; Pugh & Girod, in press; Wong, Pugh, & The Deweyan Ideas Group at Michigan State University, 2001). This paper serves as both a literature review of beauty and aesthetics in science and scientific inquiry as well as a call for the science education community to more carefully attend to these issues.

Beauty and art in the lives of scientists

An investigation of aesthetics in science faces a problem. Scientists are rarely inclined to discuss their insights, inspirations, and creative passion as they may seem less than objective and anti-intellectual in the existing, highly rational, culture of science. Often in the retelling of a scientific discovery the “human,” “creative,” “inspired,” and “passionate” sides of scientists and their stories get left out. These are often deemed unimportant or anti-intellectual, pulling readers away from the important details of theory development, research results, and answers to equations. Holton (1973) has attributed this code of silence among the scientific community to an unwillingness to disclose secrets of creativity, or diminish the discipline with tails of insights from dreams and inspiration from myth and music. This is the problem that Snow addresses in his book and an analysis of these things must overcome or sidestep this problem to find evidence for the importance of art and beauty in the lives of scientists. One solution is to find evidence in autobiographical accounts, notebooks from the lab benches of scientists themselves, and even third-party stories and re-tellings of events and discoveries in science. Luckily, there exists a wealth of each. Using these sources, the remainder of the paper serves to more thoroughly recognize the existing aesthetic space within science. It is interesting to note that many scientists quoted here are cited in secondary sources – often as excerpts from speeches, personal communications, or obscure and difficult to find references. Whenever possible efforts were taken to site sources directly but it was not always possible to do so. Again, this may be taken as further evidence of scientists’ reluctance to express these ideas in print and more mainstream venues.

Root-Bernstein, in arguing for the importance of the arts and creative expression in the lives of scientists, lists nearly 400 19th and 20th century scientists that actively participate in nonscientific forms of creativity; including 65 Nobel Prize winners (1989, p. 318-327). The list includes such notables as Thomas Huxley, who painted; Lord Rayleigh, who experimented in photography; Louis Pasteur, who was a wood and metal sculptor; Einstein and Heisenberg, who were musicians; and Marie Curie and Ludwig Boltzmann, who wrote poetry. Root-Bernstein also recognizes that many famous scientists simply do not have an artistic side, or at least choose not to exercise it, but the extraordinary list and the lesson taken from it, cannot be ignored. Many scientists gravitate toward artistic expression and Root-Bernstein suggests the reason lay in the similarities between arts and science.

One could argue that scientists are simply a subset of the general population and, like anybody else, a certain percentage of them engage in artistic expression. This is certainly true, however, following Root-Bernstein, let us extend the connection and argue that many scientists find their work beautiful and the science they do aesthetically pleasing. Recall Dirac's famous line, "It is more important to have beauty in one's equations than to have them fit the experiment" (1963, p. 47). Similarly, Simone Weil writes, "The true subject of science is the beauty of the world" (as quoted in Fischer, 1999, p. 91) and Herman Weyl follows with "My work always tried to unite the true with the beautiful; but when I had to choose one or the other, I usually chose the beautiful" (as quoted in Chandrasekhar, 1987, p. 52). Comments like these beg two questions, "What is beauty?" and more importantly for this conversation "What is beauty in science?" The first question lies in the realm of philosophy and conversations in aesthetics and aesthetic theory. This paper will not attempt a full treatment of the first question, as it is best left to philosophers. It will attempt, however, to articulate a few possible answers to the second question on the notion of beauty and aesthetics in science. As with this introduction, it will draw extensively from biographical accounts of scientists in the process of doing and analyzing science as well as from philosophers of science commenting on the process of science and scientific progress.

What is beautiful in science?

Conversations on beauty in science are as diverse and wide-ranging as conversations in aesthetics and philosophy. Various authors writing from modern, foundational stances discuss traits or qualities within objects of science as beautiful or artistic. In this regard, commonly cited qualities of beauty are simplicity of form, symmetry, pattern, and unity of structure. Similarly, Roald Hoffman, in a series of articles in American Scientist, discussed various molecular structures and in what ways he found these forms to be beautiful (1987; 1988a; 1988b; 1989). Rather than engage in a discussion of the artifacts of science and the aesthetic qualities of these artifacts the focus here is on a discussion of four themes exploring beauty in scientific ideas and experiences.

The first theme within this “scientific aesthetic space” is beauty in the representation of scientific ideas. Many scientists have expounded on the exquisiteness of powerful scientific ideas. Dirac, for example, had this to say about the general theory of relativity, "It is the essential beauty of the theory which I feel is the real reason for believing in it" (Dirac, 1980, p. 10). The second theme can be found in conversations related to cosmology, the divine structure of the universe and, in even more extreme language, beauty in knowing God’s design. Scientists and philosophers writing from this perspective often speak of tapping into some fundamental structure found in primitive archetypal universals. A third theme can be found in description of beauty in science as that which inspires awe and wonder. Philosophers would draw a distinction here between beauty and sublime but they are grouped here as categories within studies of aesthetics. A fourth theme describes beauty in the nature of the experiences themselves as scientists engage in scientific research, creativity, and experimentation. For these scientists, beauty is what's found in the act of knowing and experiencing science in intimate quality.

What follows is further articulation of each theme in an attempt to illuminate existing conversations on beauty in science. It should be noted that these themes are offered neither as a definitive review of the literature nor are they necessarily independent of one another. Explorations in this area are highly subjective and structures tend to fold as easily as they are created. Rather, these themes are offered as illustration of the breadth that exists within the scientific-aesthetic space.

Intellectual beauty: Beauty in ideas and their form

> *I once heard Dirac say in a lecture, to an audience which largely consisted of students, that students of physics shouldn't worry too much about what the equations of physics mean, but only about the beauty of the equations. The faculty members present groaned at the prospect of all our students setting out to imitate Dirac (as cited in Weinberg, 1987, p. XX).*

What passes most frequently for an analysis of beauty in science is an analysis of scientific products, artifacts, tools, images, and other "creations" of science (Tauber, 1997). This level of analysis is, arguably, not very deep and certainly misrepresents the richness of conversations in this regard. Intellectual beauty, the finding of beauty in the form and meaning of scientific ideas, was at one time, a more rich thread of inquiry and analysis.

> Nowadays the concept of intellectual beauty is not, I believe, commonly repudiated so much as neglected; few of the standard works on aesthetics pay more than lip-service to it and I know of none which has either attempted a deep analysis or given to it equal weight

> with sensory beauties in the framing of general aesthetic concepts (Osborne, 1964, p. 160).

"However, the study of intellectual beauty has fallen into disregard only relatively recently: in eighteenth-century aesthetic theory, for instance, it held an important place" (McAllister, 1996, p. 18). McAllister continues with a description of Francis Hutcheson's 18th century aesthetic theory…

> …Hutcheson endorses an epistemological tenet that was popular in his time, that the qualities of objects are distinct from, and in fact the causes of "ideas," which are the only immediate materials of sensory awareness. Beauty is such an idea, occasioned in the mind by particular qualities of external objects" (p. 18).

We turn to Hutcheson himself for further elaboration, "…the word *beauty* is taken for the *idea raised in us*, and a *sense* of beauty for *our power of receiving this idea*" (1973, p. 34). Beauty, then, for Hutcheson, is at the intersection of object and observer. Beauty does not lie alone in objects but in the observer's aesthetic perception (and cogitation) of those qualities. What qualities more commonly stimulate aesthetic perception and perception of beauty? Hutcheson continues, "The figures which excite in us the ideas of beauty seem to be those in which there is uniformity amidst variety" (1973, p. 40). Hutcheson suggests that 'uniformity amidst variety' can be found in objects, the natural world, and in intellectual ideas. Hutcheson argues that scientists perceive this uniformity amidst variety at three levels of increasing abstraction: (1) the lowest level of abstraction are the things that make up the subject matter of science - the beauty of stars layed out across the night sky or the beauty in the elegant curves of the double helix model of DNA - requires no expertise to recognize; (2) natural regularities not directly seen but illuminated by scientific theory or models - one must have some command of scientific theory -

like the astronomer who sees beauty in the regularities of celestial motion once he puts his model into action, or how plate tectonic theory helps us to appreciate the dramatic form and elegance of the landscape; (3) finally the most abstract level is in the actual theory and mathematical formulae themselves. Recall Dirac's quote on the beauty of the general theory of relativity that begins this section. Who can deny the elegance and beautiful parsimony of the equation? Certainly no more an elegant equation could exist with such explanatory power. Add Ernst Rutherford speaking in 1932…

> A well-constructed theory is in some respects undoubtedly an artistic production. A fine example is the famous Kinetic Theory of Maxwell. The theory of relativity by Einstein, quite apart from any question of its validity, cannot but be regarded as a magnificent work of art (as cited in Badash, 1987).

Without question science and scientific ideas can be viewed as beautiful, artful creations. Indeed the pursuit of this beauty may be a central motivation in the lives and inquiry of scientists. The next theme draws a more sophisticated connection between beauty and science, a connection moving further away from the concrete products of science to its intellectual and emotional manifestations.

Beauty in wonder and awe: Beauty in the sublime

> *It is because simplicity and vastness are both beautiful that we seek by preference simple facts and vast facts; that we take delight, now in following the giant courses of the stars, now in scrutinizing with a microscope that prodigious smallness which is also a vastness… (Poincaré as cited in Chandrasekhar, p. 60, 1987).*

Aestheticians are quick to remind us those theories of ugliness, perversity, and sublime lie within the realm of aesthetics as well. Burke (1990) recognizes a common characteristic in all such theories as their ability to astonish. “The passion caused by the great and sublime in nature, when those causes operate most powerfully, is Astonishment; and astonishment is that state of the soul, in which all its motions are suspended, with some degree of horror” (p. 53). Similarly, Kant describes the sublime as a “feeling of grandeur of reason itself and of man’s moral destiny, which arises in two ways: (1) When we are confronted in nature with the extremely vast (the mathematical sublime), our imagination falters in the task of comprehending it….” For example, in teaching concepts in astronomy, geology, and biology, it becomes helpful for students to appreciate the vastness (or minuteness) of extremely large and extremely small numbers to develop an adequate conceptual understanding. As a science teacher myself I’ve taught a lesson in which students construct a ‘tapestry’ of one million dots (66 2/3 pages of 15,000 dots taped together). Most students, when visually confronted with a million dots find the experience to be a bit mind-boggling. A million is a number that scientists use frequently but, arguably, the average student (and adult) fails to grasp its enormity. Coming to understand the notion of ‘a million’ is a task that could qualify as experiencing Kant’s first category of the sublime – the mathematically sublime.

Kant’s second category of sublime is similar, (2) “When we are confronted with the overwhelmingly powerful (the dynamical sublime), the weakness of our empirical selves makes us aware (again by contrast) of our worth as moral beings” (Kant as cited in Beardsley, 1967, p. 28). Remembering the experience of standing at the edge of Niagara Falls comes to mind as an excellent example of this second brand of Kant’s sublime. The enormous power and thundering energy so evident at the falls almost forces one to be aware of his/her own frailty and insignificance. In fact, some of the earliest common use of the word sublime came as authors found themselves floundering to adequately describe the experience of viewing Niagara Falls.[i]

The word sublime connotes a mixture of awe, inspiration, and a bit of fear. Interestingly, we find many examples of scientists who employ sublime in descriptions of their work. For example, Heisenberg in a discussion with Einstein writes, “You must have felt this too: the almost frightening simplicity and wholeness of the relationships which nature suddenly spreads out before us and for which none of us was in the least prepared” (Heisenberg as quoted in Chandrasekhar, 1987, p. 53). Similarly, Whewell, in commenting on Newton’s *Principia* suggest an awesome admiration and trepidation at the mathematics within.

> …As we read the *Principia*, we feel as when we are in an ancient armoury where the weapons are of gigantic size; and as we look at them, we marvel what manner of men they were who could use as weapons what we can scarcely lift as a burden…(as quoted in Chandrasekhar, 1987, p. 45).

Comments such as these are certainly not new to the rhetoric of science as we can even find reference to the notion of the sublime in Plato as quoted in the Phaedrus: “The soul is awestricken and shudders at the sight of the beautiful.”

Conversations on the sublime may only peripherally relate to the notion of beautiful ideas. Ideas do not necessarily lie at experiences of the sublime so we turn now to more direct, and often neglected, conversations on intellectual beauty.

Beauty as Truth: Beauty as God’s design revealed

> *We know on excellent authority that beauty is truth, that it is the expression of the ideal, the symbol of divine perfection, and the sensible manifestation of the good (Santayana, 1955, p. 11).*

Another strand of the conversation on aesthetics in science equates beauty with truth; fundamental, God’s-eye Truth. The notion of a connection between truth and beauty has existed for centuries as indicated by the ancient Latin phrase, *pulchritudo splendor veritatis* (beauty is the splendor of truth). It is little surprise that scientists find theories and equations with an unwavering verisimilitude more beautiful or aesthetically pleasing than those with less. In the autobiography of Emily Heisenberg, she describes her husband's reflections on his career as contemplations on the beauty of the universe and quotes him as stating, "I was lucky enough to look over the good Lord's shoulder while He was at work" (E. Heisenberg, 1984, p. 143). Coming to know the divine plan or more commonly, having the divine plan revealed, is common language in scientific discovery (this lack of agency further illustrates the cosmological sense). Again, from Heisenberg,

> …one evening I reached the point where I was ready to determine the individual terms in the energy table, or, as we put it today, in the energy matrix, by what would now be considered an extremely clumsy series of calculations. When the first terms seemed to accord with the energy principle, I became rather excited, and I began to make countless arithmetical errors. As a result, it was almost three o'clock in the morning before the final result of my computations lay before me. The energy principle had held for all terms, and I could no longer doubt the mathematical consistency and coherence of the kind of quantum mechanics to which my calculations pointed. At first, I was deeply alarmed. I had the feeling that, through the surface of atomic phenomena, I was looking at a strangely beautiful interior, and felt almost giddy at the thought that I now had to probe this wealth of mathematical structure nature had so generously spread out before me. I was far too excited to sleep, and so, as a new day dawned, I made for the southern tip of the island, where I had been longing to climb a rock jutting out into the sea. I now did so without too much trouble, and waited for the sun to rise (W. Heisenberg, 1971, p. 61).

Heisenberg speaks eloquently about his progress and the ability to finally see what nature had revealed. His efforts to climb a rock to watch the sunrise further connect to the sense of grace, divinity, and spirituality. He was able to read Truth in his equations, to see clearly a world uncloaked. The allusions to God, design, and cosmology are rich and not accidental. Heisenberg's words also illustrate plainly the related notion of Truth as something revealed rather than deciphered or discovered. The lack of agency in these descriptions is apparent and further suggests revelation by none other than God.

It is difficult to ignore the vehemence by which many scientists describe their discoveries and creative insights as being almost beyond their control – perhaps as if their discoveries were simply revealed to them or uncovered, previously there but simply unobserved. To borrow from the psychologist Carl Jung, his notion of an archetype is useful here in understanding descriptions of discovery in science.

> Archetypes are like riverbeds, which dry up when the water deserts them, but which it can find again at any time. An archetype is like an old watercourse along which the water of life has flowed for centuries, digging a deep channel for itself (1968, p. 395).

Kepler foreshadowed Jung's archetypes as he described geometry as underlying the structures of the universe writing, "Traces of geometry are expressed in the world, as if geometry were the archetype of the cosmos" (Fischer, 1995, p. 52). Although Jung's psychological archetypes evade thorough description, Kepler's archetypes reveal themselves through mathematics.

Einstein, following Kepler, sought to understand God's plan of the universe and because he did not believe God allowed for chance, Einstein believed he could describe God's plan at some basic level. This led Einstein to pursue a unifying theory of physics – a blueprint for the universe. In this pursuit, Einstein too appealed to archetypal images and elements.

> Indeed, there is overwhelming evidence that Einstein wasn't too amused by the idea of the big bang, but this didn't change the fact that his vision of the world clung to something archetypal, because there are still, as in the classical age, four elements. Instead of fire, earth, water, and air we now have space, time, matter, and energy. Additionally, whereas Aristotle postulated a *prima materia*, an original material from which the archaic group of four could originate and become influential, Einstein went on the hunt for a unified field theory which took on the same task of the *prima materia* (Fischer, 1999, p. 89).

Einstein's search pushed him into unusual territory – territory bounding on spirituality, metaphysics, religion, and myth as much as physics.

> Einstein himself had continuously emphasized the psychological-spiritual components of scientific research and in response to psychologists spoke about many of the images preceding his thinking. It was difficult for him most of all to convey his thoughts to others on things he had long understood only visually, first in formulas and then in words (Fischer, 1999, p. 84).

Today we may imagine Einstein as simply a richly divergent thinker but this is not Einstein's explanation. It was his belief that the fundamental structure of the universe, of God's plan, if you will, would occasionally reveal itself to him in these archetypal images. Similarly, August Kekulé described his discovery of the molecular structure of benzene in richly archetypal language.

> I turned the chair towards the fireplace and sank into a half sleep. Once again the atoms danced before my eyes. My inner eye distinguished larger images of multiple shapes, winding and turning like snakes. And then what did I see? One of the snakes took hold of

> its tail, and the image swirled threateningly before my eyes. As if by a stroke of lightning I woke up and spent the rest of the night working on the consequences of the hypothesis (Friedrich August Kekulé as quoted in Fischer, 1999, p. 76).

Although Kekulé example seems a bit overly dramatic and perhaps fanciful, the notion of divine truth revealed is maintained. Truth and beauty can be found in knowing God's design for the universe. God's design lies in archetypal kinds of images and divine patterns of organization that can be discovered, known to already exist, simply waiting to be discovered. As with beauty in ideas, beauty in God's design for the universe is clearly a powerful and coherent theme in science and scientific inquiry. We now turn to the final theme in the analysis.

Beauty in experience: Beauty in seeing and being anew

> *For some people the contemplation of scientific theories is an experience hardly less golden than the experience of being in love or looking at a sunset (Haldane quoted in Huxley, 1991, p. 53).*

John Dewey, in his 1934/1980 Art as Experience, attempted to naturalize or return aesthetics to discussions of the ordinary or lived experience of the individual. Rather than cloister art away in museums and galleries to be viewed and evaluated, Dewey believed art should be redefined as a condition of living in the world – suggesting that one shift the question from what is art to when is art? Dewey answers his own question by offering the "having of an experience" as the working definition of art and aesthetic experience. An experience is contrasted with ordinary experience and is identified as having a series of qualities including (1) the fusion or intermingling of thought, emotion, and action; (2) the expansion of one's perception literally creating new ways of seeing the world, and; (3) an increased feeling of value for this newfound perspective. The process of having an experience typically unfolds through a transaction between the person and the world in which each emerge as different than before the experience. We see these Deweyan qualities of experience in science and science inquiry as well. From Feynman,

> The world looks so different after learning science. For example, trees are made of air, primarily. When they are burned, they go back to air, and in the flaming heat is released the flaming heat of the sun which was bound in to convert the air into tree. [A]nd in the ash is the small remnant of the part which did not come from air, that came from the solid earth, instead. These are beautiful things, and the content of science is wonderfully full of them. They are very inspiring, and they can be used to inspire others (Feynman in National Academy of Science, 1995).

Another example from Boltzmann in which he comments on artistry of the mathematics of Maxwell uses the metaphor of musical performance as an experience.

> Even as a musician can recognize his Mozart, Beethoven, or Schubert after hearing the first few bars, so can a mathematician recognize his Cauchy, Gauss, Jacobi, Helmholtz, or Kirchhoff after the first few pages. The French writers reveal themselves by their extreme formal elegance, while the English, especially Maxwell, by their dramatic sense. Who, for example, is not familiar with Maxwell's memoirs on his dynamical theory of gases?…The variations of the velocities are, at first, developed majestically; then from one side enter the equations of state; and from the other side, the equations of motion in a central field. Even higher soars the chaos of formulae. Suddenly, we hear, as from kettle drums, the four beats "put n = 5" The evil spirit V (the relative velocity of the two molecules) vanishes; and, even as in music, a hitherto dominating figure in the bass is suddenly silenced, that which had seemed insuperable has been overcome as if by a

> stroke of magic. … This is not the time to ask why this or that substitution. If you are not swept along with the development lay aside the paper. Maxwell does not write programme music with explanatory notes… One result after another follows in quick succession till at last, as the unexpected climax, we arrive at the conditions for thermal equilibrium together with the expressions for the transport coefficients. The curtain then falls (Boltzmann as quoted in Chandrasekhar, 1987, p. 53)!

Both Feynman and Boltzmann describe understanding the world differently and more richly as a result of understanding science and mathematics. Through the having of an experience, in which powerful science ideas are at the center, both person and world emerge as different. This fusion between object and observer, thought and emotion, and action and reflection has been discussed elsewhere as a condition of synaesthesia (Girod, Rau, & Schepige, 2003; Lemley, 1999; Odin, 1986) and literally means the blending of senses and cognition to create a heightened sense of awareness and perception. Root-Bernstein elaborates, "Scientists…feel what the system they are studying does. They transform the equations into images; they sense the interactions of the individual atoms; they even claim to know the desires and propensities of the genes (1997, p. 66). This is, perhaps, an extreme example of the having of an experience in science but certainly illustrates an essential quality of scientific discovery, inquiry, appreciation, and understanding.

Recall the precious "a-ha" moments in your own emerging understanding of scientific ideas. I can recall vividly standing on a gravel bar at the edge of a swift river and turning to look upstream just as small portion of the riverbank slumped off into the swirling water. The earth material colored the water brown and sent it in swirling eddies only to arrive at my feet to be re-deposited in the bar on which I was standing. Though I had been studying geology for some time I had never before understood so clearly that there are processes that create as well as those that destroy earth's features. From that moment I began to see geologic processes as a delicate balance between creation and destruction and was carried by my newfound insight to reorganize my teaching of geology around these ideas (Smith & Girod, 2003). Science is replete with powerful ideas that have the potential to lead us into Deweyan experiences if we are open to them and allow them to unfold. We will return to these analyses of science and beauty in experience in the section linking aesthetic experiences and science learning.

Beauty in science education

It is common parlance in education to describe the sociocultural contexts in which science and scientific inquiry exist (Cole, 1996; Lemke, 2001). Despite this, there exists, what has been characterized as, "science wars" between realist studies (Koertge, 1998; Latour, 1999) and constructivist analyses of science. Whether or not art and aesthetics should, or does, play a role in scientific inquiry goes at least as far back as Dewey – as do so many issues in education. Most Dewey scholars recognize his ideas as post-positivistic but others push deeper suggesting that Dewey believed fundamentally in the role of aesthetics and the critical qualitative aspects of inquiry (Garrison, 1997; Johnston, 2002).[ii] It is with an endorsement from Dewey, as well as the pages of recognition from scientists given previously, that we move forward to explore how these issues might inform teaching and learning in the sciences. What is curious, however, is that science education has been hesitant to capitalize on the power and compelling nature of these connections (Flannery, 1991) beyond what could be characterized as superficial linkages between art and science found in many curriculum materials. As many psychological constructs are complicit in a full comprehension of science and inquiry and its relationship to aesthetics and learning, it is necessary to attempt some organization or categorization.

Related but tangential conversations

We might examine first, a set of tangential conversations related to emotion, perception, transfer, and out-of-school experience. For example, Zembylas (1998, 2002, 2005) has achieved wonderfully rich descriptions of the role that emotion plays in science teaching and learning. These analyses are particularly keen in their attention to the interplay between emotions and epistemological beliefs and the impact of these on decisions about curriculum, instruction, and resulting student learning. If the science education community begins to attend more carefully to the role of art, aesthetics, and beauty in science teaching and learning, we will surely need to deepen our understanding of the role of emotions just as Zembylas has done.

Central to Dewey's vision of science and inquiry is the role of perception (1934/1980) and what function it must play in coming to understand the world differently – in scientifically accurate and aesthetically powerful ways. A small number of science educators have written in this area calling attention to pedagogies that highlight the role of perception (Sullivan, 2000). Flannery, in her column in the American Biology Teacher, has also occasionally highlighted the role of perception in developing scientific understanding (1998; 2003). As observation is central to inquiry, this is a sensible connection. However, only a small number of science educators have stressed deep observation as a means to deepen the aesthetic experience and, in turn, the learning of science through what has been called "re-seeing" (Girod, 2001a; Pugh & Girod, in press). These authors describe re-seeing as the process of seeing the world anew through lenses of powerful scientific ideas like Newton's Laws (Pugh, 2004) and erosion (Girod & Wong, 2002). Instances of re-seeing irrevocably transform one's visions and understanding of the world in aesthetic yet scientifically important and accurate ways. The connection to science learning is obvious.

We know a great deal about how students learn and how they apply knowledge and skills in school and work settings. For whatever reason, however, science educators have failed to study diligently how learners use their knowledge in out-of-school settings (Pugh & Bergin, 2005) when these may be the uses that matter most. Studies of science learning in informal settings often cite museum and field trip research (Chamberlain, 1987; Crane, Nicholson, Chen, & Bitsgood, 1994; Falk, Martin, & Balling, 1978; Nespor, 2000) but there are very few studies that explore whether or not learners chose to employ their knowledge, unprompted, in settings outside of school (Falk, 2001; Ramey-Gassert, 1997). It may be, though, that these settings are precisely the locations most ripe for the intersection of scientific and aesthetic knowledge and experience. More work is needed in this area.

Awareness building

The most common conversations connecting science and art, aesthetics, and beauty are what could be called awareness-building conversations. These are, in my opinion, relatively superficial calls to alert students to the artistic aspects of science, scientific products, concepts, and processes. Curriculum designers often appeal to left brain/right brain descriptions of the mind, multiple intelligences theory, and learning styles when arguing for integration of art and science. The implication is that arts-science integration is important because it may allow learners with strengths in areas other than logical-mathematical analysis to be successful in science. What most commonly emerges are fairly innocuous but perhaps important attempts like allowing students to color their scale drawings of planets and to decorate with tissue paper models of jungle animals (Gooden, 2005; Stellflue, Allen, & Gerber, 2005). Hoffman's essays in which he highlighted the aesthetic elements in molecular structures, though more sophisticated than tissue paper animals, falls into this awareness building categorization. Others have highlighted the aesthetic elements in chemistry (Craig & Kravetz, 1993), biological inquiry (Flannery, 1993), and the design of scientific instruments and tools (Resnick, Berg, & Eisenberg, 2000) and a fair bit of work has been done highlighting the shared processes involved in science and art such as observation, analysis, and inference (Hunsinger, 1973; Oppenheimer, 1979; Rommel-Esham, 2005). There has emerged recently, however, a small number of theoretical and empirical studies working toward the systematic connection of art, aesthetics, beauty and science teaching and learning. These studies are the most sophisticated in their level of connection between aesthetics, experience, and science so will be discussed in most detail.

Linking aesthetic experiences and science learning

Pugh (2002; 2004) draws from Dewey's (1934/1980) aesthetic theory and the power of transformative experiences. Though Dewey himself never systematically applied his aesthetic theory to teaching and learning, Jackson (1998) has done so, powerfully highlighting the role that aesthetic experience can have in changing perception, increasing value, and deepening understanding. Girod and Wong (2002) and Pugh (2004) have used case studies to illustrate the nature and power of these transformative, aesthetic experiences in which learners cannot help but to see, think, and act differently as a result of learning about powerful science ideas. For example, after learning about erosion, one fourth-grade girl stated, "We used to sing and dance around the school at recess but yesterday we walked around the building looking for evidence of erosion." Clearly powerful learning has occurred when students chose inquiry over singing and dancing (Girod, 2001b).

Girod and Wong (2002) and Girod, Rau, and Schepige (2003) identify several qualities or criteria of aesthetic experiences derived from powerful scientific ideas. These qualities include (1) *transformative* which implies the person exits the experience different than upon entry – as a person who now cannot help but to see the world through the lens of a powerful scientific idea. (2) *Unifying*, in that this science lens affords a re-organization of world and sheds new and deeper meaning upon the world and its processes. Finally, (3) *compelling and dramatic* characterizes these experiences because learners are so emotionally connected through interest, perception, even identity and efficacy beliefs (Girod, 2001b) as to be moved to apply these new ideas to out-of-school experiences. Pugh (2004) describes similar outcomes of these experiences describing *motivated use*, *expansion of perception*, and *experiential value*. These two frameworks share many similarities, most importantly, that they are fairly close readings of Dewey's aesthetic theory and its application to science learning.[iii]

Teaching for transformative, aesthetic experiences

Though many teaching strategies could be inferred from Dewey's (1934/1980) aesthetic theory or from Jackson's (1998) expansion upon it, only Pugh and Girod (in press) have written clearly about strategies for organizing curriculum and implementing instruction in ways that are more likely to bring about transformative, aesthetic experiences. Their analysis is divided into two sections (1) crafting ideas out of concepts and (2) scaffolding experience. Each is discussed briefly.

Crafting ideas out of concepts

Dewey (1986) drew a distinction between *concepts* – which might be roughly equated to the bold-faced words that so liberally populate science textbooks – and *ideas*, which for Dewey were efferent, plans of action, that lead students into the world, poised for transformative experiences. It may also be useful to think of ideas as lenses through which to view the world anew. The challenge for teachers is to draw upon bold-faced words, content standards, or other, more traditional sources, and re-animate these into Deweyan ideas or lenses that fundamentally transform the perceptions, actions, and understandings of the world for the learner. Pugh and Girod (in press) suggest several strategies such as considering concepts in their historical context. For example, most earth science textbooks acknowledge that, at one time, man believed the earth was the center of the solar system – but that this geocentric model was replaced by a heliocentric model. Geocentric and heliocentric appear as bold-faced words, unfortunately, completely removed from the fundamentally transformative power of these ideas at the time of their original use. Afterall, this shift from geocentrism to heliocentrism displaced man (actually Rome) as the centerpiece of God's design and shook Christian beliefs to the very core. Placing these bold-faced words back in this historical context is one path toward shifting from concepts back to ideas. Pugh and Girod also describe the power of metaphor in capturing the essence of scientific ideas. For example, *erosion as a war* characterizes the essential struggle between forces that lift the earth's crust and those that denude it (Girod & Wong, 2002). Also, *atmosphere as ocean of air* characterizes the thickness, currents, pressure, density, and pressure gradients that exist in both oceans and atmosphere (Girod, 2001b). These metaphors can also serve effectively as lenses through which learners can view the world in new ways, leading to transformative, aesthetic experiences.

Scaffolding experience

Pugh and Girod (in press) go on to describe the more interpersonal components of teaching for the goal of transformative, aesthetic experiences in science. Learning with this goal in mind is significantly different from most learning occurring in schools today and students may need more explicit modeling from their teacher if they are expected to reach these same levels of experience. Pugh and Girod share several accounts of teachers who model the power of scientific ideas in their own lives – how these ideas help them to think, see, and feel differently about the world, their place in it, and the associated aesthetic affordances.

The lessons available to those interested in teaching for transformative, aesthetic experiences in science are twofold. First, craft ordinary science content into powerful ideas or lenses through which to view the world differently. Second, model the use of these lenses and scaffold students' attempts to do the same. These are perhaps rough guidelines for connecting aesthetic experience and science teaching and learning. Clearly more work is needed in this area.

Lessons learned

The lessons to be gleaned from these analyses are threefold: (1) Linking science and art makes sense in developing both analytic lenses for the analysis and exploration of research questions in science and science education. (2) We must continue to formulate theories of learning science that incorporate an appeal to the aesthetics in science, expanding on the initial work described here. The work of Girod (2001b) suggests that learning science through a gateway of aesthetics affords more and deeper scientific understanding. (3) Finally, science education should work to systematically explore the development of pedagogies designed to capitalize on the scientific-aesthetic spaces and potential motivational energy discussed above.

It should be recognized that research on the nature of science has attended to aesthetics for some time (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002) in terms of the role of imagination and creativity. Few efforts, however, have been made toward systematic attention to this area. As many issues begin to become bound together such as motivation and engagement, learning and development, in school learning and out-of-school transfer, this can quickly become a thoroughly interdisciplinary investigation. Perhaps this paper can also be viewed as a call for more interdisciplinary research to properly tap the potential of art, aesthetics, beauty and science teaching and learning.

Conclusion

This paper is neither a comprehensive overview of the aesthetic space within science nor its relationship to philosophy, aesthetic theory, or educational psychology. It is, however, a call for science educators to more systematically attend to, study the results of, assist teachers in teaching for, and weighing effectiveness as, at least in part, the recognition of the relationship between aesthetics and science. I close with these lines from Root-Bernstein, “A person who cannot appreciate the beauty in a piece of art, or in a piece of science, does not understand it any more than if they cannot appreciate its intellectual content.” And similarly, “Students rarely, if ever, are given any notion whatever of the aesthetic dimension or multiplicity of imaginative possibilities of the sciences, and therefore, no matter how technically adept, can never truly understand or appreciate them” (1997, p. 63-64). With Root-Bernstein, I believe that understanding must incorporate elements of aesthetics and aesthetic appreciation through aesthetic experience or truly powerful learning simply will not occur.

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Endnotes

[i] I heard this once on a television program describing the natural history of the Niagara Falls region. I am unable to provide a reference but I find the assertion quite plausible.

[ii] A more detailed accounting of these issues and the associated process of abduction (as opposed to induction or deduction) as they relate to Dewey's notion of scientific inquiry can be found in Prawat (1999).

[iii] A more creative application of Dewey's aesthetic theory to learning can be found in Wong (in press) as he explores the boundaries of these ideas and the psychological processes involved in truly transformative, aesthetic experiences.