1. A Review of Studies Demonstrating the Effectiveness of Integrating Arts, Music, Performing, Crafts and Design into Science, Technology, Engineering, Mathematics and Medical Education, Part 1: Summary of Evidence that Integration Is Professionally Useful and Effective.

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Abstract: This is Part 1 of a three part analysis of studies concerning useful ways in which visual and plastic arts, music, performing, crafts, and design (referred to for simplicity as Arts-Crafts-Design or ACD) may improve learning of Science, Technology, Engineering, Mathematics and Medicine (STEMM) and increase professional success in these subjects. We address: 1) what are the ways in which arts and STEM can interact fruitfully; 2) which of these have been explored using well-devised studies and what do these tell us about efficacy; 3) where are the gaps (and therefore the opportunities) that can readily be addressed by new studies; and 4) what kinds of methods can be used to generate reliable data? Part 1 summarizes studies demonstrating that ACD are valuable to STEMM professionals, providing a taxonomy of twelve fundamental ways that STEMM professionals employ ACD ranging from shared mental "tools", creative processes, and aesthetic considerations, to the discovery of novel problems and phenomena, analogies, materials, principles, methods and even mental recreation. Not all STEMM professionals find ACD useful; those who do believe that all knowledge can be unified through "integrated networks of enterprise"; and integrators are very significantly more likely to achieve greater success than those who do not. Moreover, STEMM professionals who use ACD always connect disciplines using specific ways of thinking, skills, materials, models, analogies, structures or processes. These findings make the issue of near and far transfer between ACD and STEMM disciplines irrelevant: the question of far transfer reduces to whether specific links between the two can be found that create direct "near-transfer" bridges between "far-apart" subjects.

"The greatest scientists are artists as well."

~Albert Einstein, pianist and violinist, Nobel Prize, Physics, 1921.
In: The Expanded Quotable Einstein, 2000, pp. 155, 245.

"The creative scientist needs… an artistic imagination."

~Max Planck, pianist, Nobel Prize, Physics, 1919.
In: Autobiography, 1949, p. 14.

"If I were asked to select the best chemist in any gathering,
I should find out first who played the 'cello best."

~T. W. Richards, Nobel Prize, Chemistry, 1914, cellist and painter.
In: Gordon, 1932, 366.

Introduction: Why Integrate Arts, Crafts and Design in Science, Technology, Engineering, Mathematics and Medical Education?

Various studies that will be reviewed below suggest that training in arts, crafts and design (ACD) may improve the learning and performance of science, technology, engineering, mathematics and medical (STEMM)subjects, but available research on the best ways to integrate with STEMM subjects is sparse and it is evident that there are many ways that such integration can be done badly or even harmfully. To understand how best to integrate ACD with STEMM it is therefore necessary first to understand the nature of the skills and knowledge that each requires in and of itself and among these, the ones that may contribute fruitfully to their combination.

From the very first introduction of STEMM subjects into school and college curricula during the late nineteenth century, people involved in science education, policy, psychology and other disciplines have tried to characterize the kinds of skills and knowledge required to teach STEMM subjects to general students and more particularly to train creative STEMM professionals. Thomas Henry Huxley, the biologist most responsible for the introduction of science as a required subject in secondary and collegiate education in the United Kingdom, surprisingly tied ability in scientific research to competency in arts and crafts. A talented watercolorist, a fine draughtsman, and fond of singing, he insisted that any school or college introducing science into its curriculum make art and music mandatory as well. When he founded the Department of Science and Art at the Normal School of Science in South Kensington (which was later absorbed into the Imperial College of Science and Technology and then the University of London), he required his biology students (who notably included the novelist H. G. Wells) to take painting and drawing lessons (Bibby, 1960).

The requirement had its purpose. As Huxley (1900) argued, "The business of education is, in the first place, to provide the young with the means and habit of observation; and secondly to supply the subject-matter of knowledge either in the shape of science or of art, or of both combined" (v3, 175). How, he asked, can a scientist be trained in the habits of observation if they do not train their eyes, ears, and hands through art and music?

> I should make it absolutely necessary for everybody, for a longer or shorter period, to learn to draw… you will find it an implement of learning of extreme value. I do not think its value can be exaggerated, because it gives you the means of training the young in attention and accuracy, which are the two things in which all mankind are more deficient than in any other mental quality whatever..... You cannot begin this habit too early, and I consider there is nothing of so great a value as the habit of drawing, to secure those two desirable ends. (v3, 183-184; See also, v3, 409-410)

In addition to the arts, Huxley also advocated an education that required the development of technical skills. One must, he argued, have direct hand knowledge of things to understand them: "Clever talk touching joinery will not make a chair; and I know that it is of about as much value in the physical sciences. Mother Nature is serenely obdurate to honeyed words; only those who understand the ways of things, and can silently and effectually handle them, get any good out of her" (Huxley, v3, 408). Huxley spoke from experience, asserting in an essay on "Technical Education" in 1877, that although his title proclaimed him a biologist, he was also a "handicraftsman":

> I am, and have been, any time these thirty years, a man who works with his hands… I do not say this in the broadly metaphorical sense... I really mean my words to be taken in their direct, literal, and straightforward sense. In fact, if the most nimble-fingered watchmaker among you will come to my workshop, he may set me to put a watch together, and I will set him to dissect, say, a black beetle's nerves. I do not wish to vaunt, but I am inclined to think that I shall manage my job to his satisfaction sooner than he will do his piece of work to mine. (v3, 406).

As a result of Huxley's arguments, many universities founded, and still retain, a "College of Arts and Sciences", though most have forgotten the history and rationale that led to this particular combination of disciplines.

Unfortunately, Huxley's synthesis of arts, crafts and sciences was rapidly undermined in the UK by disciplinary specialization and the social stigmas that separated people who worked with their hands from "intellectuals" who did not. The separation was less evident in the United States, which lacked a class-based intellectual elite and derived a large portion of its emerging scientific talent from farming and industrial backgrounds in which handwork was highly valued. When World War II created the need to recruit scientists for war work, these social and national differences had very practical implications that became the focus of a mammoth study led by the Nobel laureate (Physics, 1915) William Lawrence Bragg. Bragg, himself an excellent craftsman fully capable of making his own laboratory equipment and also a talented painter, was put in charge of a group of eminent scientists (including the physicist-novelist C. P. Snow of "Two Cultures" fame) who interviewed and placed every scientist in the UK into some type of war work.

Bragg and his colleagues quickly realized that US scientists were outstripping UK scientists in devising new inventions such as radar, for the obvious reason that very few UK scientists had any practical skills. Bragg (1942b) concluded in a public report that "the training of our physicists is literally too academic." Like Huxley, he believed that arts and crafts were germane to scientific education. Thus, when the UK government threatened to shut down all arts schools to free up manpower for the war, he argued strongly against the move because "more study of arts subjects… [will foster] those who will later follow science" (Bragg, 1942b). In 1963, he expanded his argument to include craftsmanship along with the arts as necessary skills for budding scientists, maintaining that "practical work is far more effective than book-reading in giving them [future science students] a feel for science. School training provides the background.... but a perhaps even more important incentive comes from their hobbies…" (Bragg, 1963).

Among the Nobel Laureates who joined Bragg in his campaign to make scientific training more practical was P. M. S. Blackett (Physics, 1948), who wrote an essay on the necessity of arts and crafts in the laboratory: "The experimental physicist is a Jack-of-All-Trades, a versatile but amateur craftsman. He must blow glass and turn metal…he must carpenter, photograph, wire electric circuits and be a master of gadgets of all kinds; he may find invaluable a training as an engineer and can profit always by utilising his gifts as a mathematician" (Blackett, 1933, 67). Similarly, as recently as 2012 Professor Heinz Wolff of the British Institute of Engineering and Technology bemoaned the “death of competence” due to the loss of arts and handicrafts in education:

> Apart from typing, we don’t use our hands. Girls don’t embroider; boys don’t play with Meccano [Erector sets]. With these things you effectively develop an eye at the end of the finger, and you do this when you’re seven years old. And it’s really very clever. But it’s gone…Our engineering students can’t make things. They might be able to design things on a computer, but they can’t make things. And I don’t believe that you can be an engineer properly, in terms of it circulating in your blood and your brain, without having a degree of skill in making things. (cited in Borovik, 2012)

Bragg, Blackett, and Wolff are joined by the British embryologist C. H. Waddington, who was also a talented dancer, artist, and historian. in his book *Behind Appearance* (1969), a study of the interactions between sciences and arts in the 20th century, Waddington asserted that the hands-on requirements of science and art profoundly connected the two domains:

> There is a peculiar affinity… between the experimental scientist and the painter in their experience of coaxing parts of the material world – paint, canvas, stone, or ultramicrotomes, bubble-chambers or simple hypochondriac embryos – to do what they want them to do. Painters and laboratory scientists have to recognize and respect the ‘green-finger’ ability of some people to pull things off when others just make a mess…. [This] affinity between technical mastery in painting and in laboratory work is much closer than between either of them and ‘writing well’. All three, including writing like an angel, depend mainly on non-conscious mental processes; but outstanding execution in scientific experimentation and painting have in common a dependence on ability -- probably ultimately muscular -- to handle the physical stuff of the world in a way which is not at all demanded by literary composition. The values which some modern painters see in calligraphy are already part of the scientific ethos. (p. 158)

Physicist, novelist, and historian of technology Mitchell Wilson (one of Enrico Fermi’s valued collaborators) provided a similar explanation for why such broad skills are necessary to STEMM professionals. Beyond basic technical knowledge and mathematical skill, the scientist required a heightened communicative skill:

> The particular kinds of sensibilities required by a scientist… [include an] intense awareness of words and their meanings.... [The scientist must be] capable of inventing new words to express new physical concepts. He must be able to reason verbally by analogy.... The scientist must also think graphically, in terms of dynamic models, three-dimensional arrangements in space... Formulas and equations printed on a two-dimensional page have three-dimensional meaning, and the scientist must be able to read three dimensions to 'see the picture' at once…. [for] unless a man has some kind of spatial imagination along with his verbal sensibility, he will always be – as far as science goes – in the role of the tone-deaf struggling with a course in music appreciation. (Wilson, 1972, 11-12)

Wilson incorporated this insight into his novels. In Live with Lightning, for instance, the physics student Erik Gorin, develops a literal "feel" for materials in the invention and building of scientific devices:

> Copper was so soft and chewy that one had to be tender with it. Brass was good and brittle and could be worked with relaxing ease. Steels were unpredictable; some tough, and others soft with knots of hardness spread throughout like seasoning. Whenever he had to work on nickel, he approached the job with dread. He preferred to work with glass because glass blowing… was an artist's medium. One came to it with no tools but one's breath, an eye, a sense of timing, and the jets on the torch (Wilson, 1959, 71).

Beyond Anecdotes to Formal, Large-Scale Studies of the Relationship between ACD and STEMM

The forgoing, qualitative accounts of what makes for the most creative or innovative STEMM education are, of course, biased by personal experience. Nevertheless, it is striking that all individuals thus far cited remark that arts, crafts, design, and even literary skill may be invaluable for the highest levels of achievement. Even more striking, various larger, controlled studies have validated these individual observations. For example, in 1962, David Saunders of the Educational Testing Service performed a study of engineers working for five industry powerhouses: AT&T Bell System, Detroit Edison, B. F. Goodrich, IBM and Westinghouse. He found that those engineers who excelled at research and innovation could be distinguished from other engineers working on similar development and applications problems. They displayed a higher tolerance for ambiguity, greater empathy for other people, and finer skill at inducing patterns. In short, they were "less practical" and "more artistic" than their colleagues (Saunders, 1963, 326).

Two years later, Joseph Rossman published a study of inventors with multiple patents, characterizing them in many of the same terms—practical, analytical, self-critical and persistent. In addition, they were "ingenious," "imaginative," of an "artistic or poetic nature," "observant," "unusually cultured," and "mechanically skilled" (Rossman, 1964, 35-55). Root-Bernstein, et al. (2013) have confirmed these previous studies, demonstrating that professional engineers are significantly more likely to have avocations involving crafts, music, visual arts, and photography than are members of the general public. Moreover, as Saunders (1963) had found previously, the most innovative engineers, those who had produced five or more patents or had founded at least one company, were significantly more likely than those engineers who had not to participate in crafts, photography, and fine arts over their lifetime (Root-Bernstein, et al., 2013).

Studies of scientists and mathematicians have yielded findings similar to those for engineers. P. J. Möbius (1904) (the nephew of the famous mathematician who invented the Möbius strip) reported in a study of working methods that the majority of mathematicians he surveyed engaged in musical, literary, poetic, and artistic avocations. His study is apparently the first to support the claims of various eminent mathematicians that an artistic sensibility lay at the heart of their creativity: “Mathematics and music! The most glaring possible opposites of human thought! and yet connected, mutually sustained! It is as if they would demonstrate the hidden consensus of all the actions of our mind, which in the revelations of genius makes us forefeel unconscious utterances of a mysteriously active intelligence,” proclaimed the physicist and musician Hermann von Helmholtz (1857). “May not Music be described as the Mathematic of sense, Mathematic as the Music of reason?” asked mathematician-musician Joseph Sylvester. “The soul of each the same! Thus the musician feels Mathematic, the mathematician thinks Music” (Sylvester, 1864).

In the same vein, Sofia Kovalevskaya, celebrated mathematician as well as poet and playwright, wrote that mathematics is a “science [that] requires great fantasy, and one of the first mathematicians of our century [Weierstrass] very correctly said that it is not possible to be a complete mathematician without having the soul of a poet” (cited in Kennedy, 1983). Studies following in the footsteps of Möbius also found that mathematicians had a hand in music at much higher rates than was common among the general population or even among other scientific specialists. Claparède and Flournoy (1902; 1904), for example, found that 52% of the professional mathematicians they surveyed reported music as an avocation. This figure compares with the 23% of Nobel prizewinning scientists who listed music as an avocation, 16 % of U. S. National Academy of Sciences members, and 15% of U. K. Royal Society members (Root-Bernstein, et al., 2008).

From the mid-19th century on, studies of uncontrolled, convenience samples of eminent scientists came up with similar results. Like the best mathematicians, the best scientists across many fields were more likely than not to engage in crafts, arts, and design avocations than their average colleagues. Sir Francis Galton, one of the founders of modern psychology, found that members of the British Royal Society were unusually likely to be visually, artistically, musically, and mechanically skilled; he strongly urged that students preparing for careers in science be rigorously trained in five subjects: mathematics, logic, experimental science, drawing, and mechanical skills (Galton, 1874). J. H. van't Hoff, the first Nobel Prize winner in Chemistry (1901), studied a convenience sample of several hundred scientific biographies and reported that the more creative a scientist was, the more likely he was to display his creativity in some form of art, music, invention, poetry or literary composition, as well (van't Hoff, 1878). (Van't Hoff was, himself, a flautist, poet, and artist.) Roe (1953), the first modern psychologist to study scientific creativity formally, found that members of the U. S. National Academy of Sciences were characterized by extraordinary visualization skills. Anzai (1991) found that increasingly skilled use of drawings and diagrams was a direct correlate of increasing expertise in physics. D. W. Taylor (1963) found that literary ability and experience with tools (i.e., craftsmanship) were also skills differentiating the most successful scientists from their more average peers in industrial laboratories.

Eiduson (1962; 1973) also noted that the best scientists differed from their more average colleagues in arts and literary interests. In what may be considered the first longitudinal study of scientific careers, she tracked forty male scientists, including four men who won Nobel Prizes, two more nominated for that Prize, eleven members of the U. S. National Academy of Sciences, two dozen average scientists, and three who failed to obtain tenure. Over a 30-year period, data revealed, individual participation in artistic, musical, and literary pursuits, in crafts, and in physical recreations correlated highly with various measures of career success (Root-Bernstein, et al., 1995). Those scientists who painted, drew, sculpted, photographed, wrote poetry or engaged in wood- or metalworking were significantly more likely than the rest of the scientists in the group to have authored very highly cited articles (>100 citations in a 10-year period – a figure that included all of the Nobel laureates and members of the National Academy). The most successful of the scientists were what Eiduson herself characterized as "gentlemen of science," meaning erudite, cultured individuals who were clearly distinct in their range of learning and non-academic pursuits from the average scientist.

Subsequent studies of larger groups of scientists using various types of control groups have yielded similar results. Root-Bernstein, et al. (2008) compared the avocational interests of all Nobel laureates in the sciences (to 2000) with those of an average group of scientists (represented by Sigma Xi, the research organization that any working scientist may join) and with those of the general U. S. public. On the one hand, the avocational interests of average scientists were not significantly different than those of the public. On the other, Nobel laureates proved at least twice as likely to be photographers or musicians as the typical scientist, and between fifteen and twenty-five times as likely to participate actively in visual and plastic arts, in crafts such as woodworking and metalworking, in performing arts such as acting and singing, and in creative writing. Indeed, a substantial subset of these Nobel laureates not only had arts and crafts avocations, but engaged in concurrent or second professional careers in the arts or literature. Members of the U. S. National Academy of Sciences and the U.K. Royal Society engaged, on average, in music, arts, and crafts at about half the rate found among Nobel Prize winners, but still about twice the rate found among average scientists and the general public. In other words, the more time devoted to ACD across a lifetime, the greater a scientist's probability of achieving scientific eminence.

Root-Bernstein, et al. (2013) also investigated the avocations of mid-career Michigan State University Honors College graduates who had gone on to have careers in the sciences. Those who had produced patents or founded scientific companies (i.e., entrepreneurial innovators) were compared with those who had done neither. The entrepreneurial innovators were significantly more likely to display sustained participation over their lifetimes in drawing and photography, in musical composition, in dancing, and in crafts such as mechanics, woodworking, and electronics than their equally successful but less innovative cohort. Interestingly enough, playing a musical instrument as opposed to composing music correlated negatively with patent production in this study, an observation also made during the longitudinal analysis of a very different type of population.

In a large sample of American youth (N=7,148) surveyed in 1979, Niemi (2015) tracked over time how "leisure time interests in the arts relate to entrepreneurship and innovation at work… Self-reported interest in visual arts, music, and literature was analyzed in relation to occupational innovation as indexed by history of business ownership, contributions to work leading to patent applications, and considering oneself an entrepreneur." Additionally, Niemi controlled for "personality characteristics previously suggested to underlie innovation and creativity, including self-mastery and a willingness to take risks, as well as general educational attainment and math and verbal aptitudes." By the time they were 52 years old, approximately one percent (n = 96) of participants had contributed to a filed patent application. Yet of all the factors investigated (arts interests, verbal and mathematical SAT scores, and psychological factors) only interest in visual arts (painting; drawing or prints; architecture; sculpture) proved a statistically significant predictor of that innovative behavior.

In sum, personal testimonies and sampled outcomes as presented above offer somewhat disparate evidence: musical engagement appeals profoundly to many mathematicians, yet playing an instrument in and of itself provides little benefit to entrepreneurs. It may be that unexamined qualities of ACD engagement—whether active or passive, whether conceptually relevant or irrelevant to STEMM—play as much of a role in the relationship between ACD and creative practice in the sciences as duration of engagement. At this point, such a proposition remains to be determined. What is clear at present in this: the weight of current evidence demonstrates a strong correlation between success in STEMM careers and serious, persistent avocational participation in ACD over a lifetime.

Possible Explanations of Why ACD Are Associated with Success in STEMM Careers.

Correlations are not, of course, causation. What one would like to see are interventions that demonstrate not only *that*, but also *how* ACD can improve STEMM performance. The second part of this paper will provide such evidence. First it is necessary to consider what kinds of connections or bridges one might reasonably expect between ACD and STEMM. Much as it would nice to be able to say that practicing any ACD will improve STEMM performance across the board, the evidence summarized above does not support such a conclusion. In addition to the conundrum posed by musical avocations, there are others. Craft skills (such as mechanical ability) appear to have no relationship with mathematical ability, for instance, but a relationship almost certainly exists between craft skill and inventiveness, craft skill and experimental ability. In short, it would appear that some ACD, or perhaps more particularly *some* specific types of skills and knowledge obtained through the practice of ACD, are valuable to *some* aspects of STEMM practice. We need to tease out those specific skills and aspects and the bridges that connect them.

Interview or survey responses in many of the studies summarized above provide a way forward. The kinds of connecting bridges STEMM professionals perceive between their professional work and ACD avocations or training often appear idiosyncratic (a point to which we will return below). Nevertheless, perceptions of connection do fall into about twelve relatively distinct categories that can direct further analysis of how ACD and STEMM learning might most fruitfully be integrated. Many of the articles and books cited above (especially Roe, 1951; Roe, 1953; Root-Bernstein, et al., 1995; Root-Bernstein, et al., 2008; Root-Bernstein, et al., 2013; Lamore, et al., 2013) contain multiple examples of how STEMM professionals have made these links between ACD and STEMM practices, so we will provide here only one exemplar to illustrate each interdisciplinary bridge.

- **Bridge 1. Mental skills or "tools for thinking" such as observing, imaging, abstracting, pattern recognition and pattern forming, analogizing, empathizing and playacting, body thinking, dimensional thinking, modeling, playing, transforming and synthesizing,** which are required to perform any kind of observational or experimental science (Root-Bernstein, 1989; Root-Bernstein & Root-Bernstein, 1999). Good examples of how these "tools" are recognized to be of value to STEMM professionals can be found in the descriptions of skills provided above by Huxley, Bragg, Blackett, Waddington, and Wilson. An additional study by Van Herzelee, et al. (2010) found that visuo-spatial ability, fine motor control, and imaging ability were each independently, and also as a group, predictive of endovascular surgery performance among medical student trainees.

- **Bridge 2. Experience with materials, tools and methods of using them that may then inform STEMM practices**. Alexis Carrel, the 1912 Nobel Laureate in Medicine or Physiology, "learned [as a child] the intricate stitching required for his [later surgical experiments] from the renowned lace makers of Lyon, one of whom was his mother" (Bishop, 2003, 140).

- **Bridge 3. Techniques and phenomena previously unknown to STEMM professionals.** The artist Marcel Duchamps experimented with various effects of moving images on human perception through a form of art he invented called "Rotoreliefs." Some of these effects, such as a rotating disc in which the image appears to spiral both in and out simultaneously, pose explanatory challenges for perceptual psychologists, who have used them psychology investigations (Sekuler & Levinson, 1977).

- **Bridge 4. Novel principles and structures that reveal new aspects of natural processes**. Attempts by Leonardo da Vinci to understand how to draw trees realistically led him to contemplate the principles underlying their structures. The result is something called "Da Vinci's Principle." The rediscovery of this principle in da Vinci's notebooks about a century ago led to the flowering of botanical studies around his "principle" that are ongoing today (e.g., Williams, 1965; Long, 1994).

- **Bridge 5. Recognition of unsolved problems lying at the junctions of ACD and STEMM**. Modern theories of "plication," the science of folding structures, have direct connections to investigations by STEMM professionals such as Robert J. Lang of the mathematical and physical bases of the art of origami. In turn, the elucidation of these mathematical and physical principles has led to a renaissance in origami innovations in the past two decades (see Lang's website: www.langorigami.com).

- **Bridge 6. Experience navigating the creative process more efficiently and cogently.** Georges Urbain was the discoverer of element Lutetium and also a sculptor, musician and composer who wrote of the connections between his diverse activities that, "the musician combines sounds in the same way the chemist combines substances…. It is true that musician and chemist reason in their respective fields in the same way, despite the profound difference of the materials they use" (Urbain, 1924).

- **Bridge 7. Practice in the application of transdisciplinary aesthetic principles**. Evolutionary biologist Per Olaf Wickman says it all in the preface to his book, *Aesthetic Experience in Science Education* (2006):

> In science education research there is rarely any mention of the aesthetic sides of science, and often aesthetics is pictured as other than science. However my own time as a researcher was both an intellectual and aesthetic experience. In saying this I have to stress that aesthetic experience was not simply a motivational drive for my engagement in science; it was continually present when working.

- **Bridge 8. Strategies for exploring and mastering new material efficiently**. The mother of Nobel-Prize winner Dorothy Crowfoot Hodgkin was a trained artist who taught her daughter how to draw and paint everything she observed. As part of her home schooling, Hodgkin illustrated her parents' archeological digs, especially the mosaic floors found at some of their sites. Hodgkin "began to think of the restraints imposed by two dimensional order in a plane" (cited in Ferry, 1998, 8), an exercise she subsequently associated with her ability to think about the scientific principles underlying her chosen profession, crystallography.

- **Bridge 9. Mnemonic and other mental devices that increase acquisition and retention of learned material**. Particularly common in disciplines characterized by a great deal of observational identification and/or special nomenclature, as indicated by Op Den Akker, et al. (2002):

> We describe a new method, bodypainting, to enhance courses in living anatomy… We designed a course in which the students familiarized themselves with the surface markings and subsequently painted the full organ at the site of its projection on the body surface. Based on our first experiences, we conclude that the course is a successful and enjoyable means of teaching various aspects of anatomy in relation to physical examination. This was confirmed by an evaluation among the first groups of students.

- **Bridge 10. Practice translating, transforming and transferring concepts and practices between and among disciplines**. Zoologist Jonathan Kingdon has authored a series of encyclopedias about the evolution of African mammals that many consider among the 100 most important science books of the past century (Morrison & Morrison, 1999). He began his study of animals as an artist. Indeed, he has written, "Drawing is a way of exploring. Scientists have lots of techniques. They make histograms, graphs and tables. These techniques are no different to [sic] drawing. Drawing is just as scientific" (Anonymous, 2003, 46). Explicating further, he notes that visual discoveries of form in nature translate directly to scientific concern for pattern:

> It is hardly possible to compare animals without asking questions, and drawing is an exercise in comparisons, comparing the proportions of parts with parts, parts with wholes and comparing one form with another… The comparison of forms…. raises questions, and drawing can be employed as a wordless questioning of form; the pencil seeks to extract from the complex whole some limited coherent pattern that our eyes and minds can grasp. The probing pencil is like the dissecting scalpel, seeking to expose relevant structures that may not be immediately obvious and are certainly hidden from the shadowy world of the camera lens. (Kingdon, 1983, 251)

STEMM professionals in the physical sciences similarly use art to explore "large and complicated system[s]" (Smith 1981, 9).

- **Bridge 11. Recreation (often involving re-creation) that stimulates new creation**. Frederick Banting, the 1923 Nobel Laureate who discovered insulin, wrote that some people go ‘‘for recreation and on account of high life are wreckreated, while others who go for recreation are re-created’’ (1979, 36). Banting’s own recreation was outdoor painting, which he treated as a type of research useful for stimulating new ideas.

- **Bridge 12. Recording and Communication**. Various types of dance notation have been adapted for recording animal behavior and for the study of neurological deficits on human movement (e.g., Benesh & McGuinness, 1974; McGuinness-Scott, 1981; Harrison, et al., 1992; Teitelbaum, et al., 2004; Wishaw & Pellis, 1991; Melvin, et al., 2005).

Integration of ACD into STEMM Must Be Explicit

As the examples provided above illustrate, STEMM professionals who find ACD useful are very explicit about the ways in which ACD affect their STEMM practices. Since we have provided only a handful of such examples, however, it is perhaps worth a moment to provide broader evidence of this claim.

Three studies prove particularly incisive. The first was carried out by Visher (1947) on “starred scientists” (those considered to be the most eminent) listed in *American Men of Science* in 1947. These scientists were asked whether the arts should be part of STEM education, and even though 39 percent had had no such training themselves, 80% replied “yes.” The reasons given generally involved the notion of improving skills or creative ability. A more recent study of 235 mid-career scientists and engineers were similarly asked, “Would you recommend arts and crafts education as a useful or even essential background for a scientific innovator? Why or why not?” Again, just over eighty percent of the respondents replied that arts and crafts should be part of STEMM education (Root-Bernstein, et al., 2013). The same 235 scientists were also asked, “Does your avocation or hobby— or the skills, knowledge, esthetic, social contacts, creative practices, or just plain perseverance that you have gained from it— play any role in your current vocation? If so, please explain how.” Sixty-five percent of the respondents stated that they recognized that their arts or crafts avocation stimulated their vocational practice (Root-

Bernstein, et al., 2013). These survey results provide evidence that the correlations between arts and crafts participation and career success rise above some intangible and subconscious association to explicit awareness of utility. (Conversely, scientists who found no use for the arts in their own work were also very likely to argue that arts were not useful for STEMM training.)

A third, paired study isolated certain impacts that perceptions of ACD utility had on scientific creative endeavor, suggesting that explicit awareness may in fact be necessary to activate ACD/STEMM bridges. Root-Bernstein, et al. (1993; 1995) investigated the work habits and avocations of Eiduson's forty scientists, mentioned above. (To repeat, this group was notable in having several Nobel Prizewinners and eleven members of the National Academy of Sciences at one end of the spectrum and a number of scientists who did not achieve tenure at the other.) Like the two studies summarized in the previous paragraph, this one found that adult ACD avocations were highly predictive of career success; furthermore, the most successful scientists were highly aware of the positive impact of ACD avocations on their STEMM research (Root-Bernstein, et al., 1995). Three factors shed light on the ACD-STEMM connection. First, whereas the most successful scientists uniformly avowed that their avocations (whether ACD –related or involving other activities such as politics, sports or games) were sources of inspiration for their professional work, the lowest performing scientists uniformly viewed their avocations as wholly separate and unrelated (Root-Bernstein, et al., 1995). Second, self-evaluations correlated almost perfectly with the scientist's work habits. The highest-performing scientists uniformly reported that taking time off from their vocational work was an essential strategy that they used to stimulate new ideas (i.e., they employed ACD as recreations that stimulated creation) whereas the lowest-performing scientists uniformly described time away from work as a "waste of time" (Root-Bernstein, et al., 1993, 1995). Third and finally, the highest performing scientists uniformly expressed the view that C. P. Snow's "two culture" gap was a fallacy that the best scientists bridged by being themselves artists, musicians and writers, while, once again, the lowest-performing scientists were equally certain that the "two culture" gap was real (Root-Bernstein, et al., 1995).

The most successful and innovative STEMM professionals not only engage in ACD avocations, they explicitly perceive these avocations as integral parts of a holistic approach to their professional lives. Such integration of skills and knowledge from diverse life experiences has been noted previously by several investigators attempting to understand the cognitive bases of creative ability. John Dewey noted that creative people universally constructed integrated "activity sets" that linked their apparently diverse interests (Dewey, 1934; King, 1996, 6-8, 52, 228-29, 259). Howard Gruber explained Darwin's amazingly integrative insights as resulting from integrated "networks of enterprise," in which every method and fact that he learned in each of the many disciplines he studied was linked to those he learned in every other (Gruber, 1989). Root-Bernstein has called this phenomenon "correlative talents" to emphasize that innovators must also discover the *functional relationships* between sets or networks of activity (Root-Bernstein, 1989, 313-315).

We are now ready to draw some pedagogical ramifications. Simply providing STEMM students with ACD training will, in all likelihood, be no more effective in improving STEMM education than the current system of college "distribution requirements." *If students and teachers do not recognize some STEMM-derived need that ACD training can supply, or if they find ACD training unappealing or a waste of time, then not only will integration fail to occur, but negative lessons might well ensue!* Effective integration of ACD into STEMM education must therefore include explicit recognition of those interdisciplinary bridges that make ACD training functionally effective in STEMM contexts and personally valuable. The goal of ACD-STEMM integration must be the formulation of individualized integrated networks of enterprise, not merely the integration of artists or art lessons into science classrooms. We will return to this subject at the end of our second essay in evaluating the characteristics of the most successful pedagogical programs integrating ACD into STEMM education.

ACD-STEMM Connections Are Specific, Not General

In light of the many very specific and varied ways in which STEMM professionals have utilized ACD as adjuncts to their professional work, it becomes clear that an enlightened approach to integrating arts, crafts and design into STEMM education requires two things: 1) breaking down the specific types of skills or knowledge developed in any particular art, craft or design project and 2) ascertaining how these may overlap with skills and knowledge required in a STEMM subject. Hypotheses such as "arts will make STEMM professionals more creative" are too broad and amorphous to be testable or implementable. A more nuanced approach that examines specific types of bridges between ACD and STEMM subjects is required. For example, Ainsworth, et al. (2011) and Quillin and Thomas (2015) have both provided excellent analyses and summaries of research concerning the many ways that a single artistic process, in this case drawing, can be implemented within a STEMM context. A range of implementation types (from teacher-presented to teacher-produced to student-produced, with many variants in between) effect a range of learning outcomes. Drawing can be employed to improve the interpretation of visual information, to enhance motivation to study a STEMM subject, to elicit and train students' mental models and model-based reasoning, to enhance observational skill, to connect concepts and ideas (e.g., through mental images or "mind maps"), to emphasize science as a process skill rather than as a set of facts, to display quantitative information and communicate it more effectively, to teach design principles for scientists, or to enhance visuo-spatial ability (references to formal studies in Quillin & Thomas, 2015).

While simply drawing for the sake of drawing can *potentially* provide transferrable skills appropriate to each of these goals (as we will demonstrate below), it should be obvious that specifically designing drawing lessons *for the purpose of developing one or a small subset of these goals* will be a far more effective pedagogical strategy. Skill and knowledge transfer are much more likely to occur when student and teacher both understand and are explicit about the purpose for which a lesson is being carried out. In addition, the use of an art or craft to achieve a particular pedagogical goal must be appropriate to that purpose. It makes no sense, for example, to use dance to try to improve the memorization of lists of scientific terms, to improve observational skill in the use of a microscope, or to model static scientific objects. Dance has no characteristics that make it appropriate for such uses. Dance can, however, help students model kinetic processes, transform such processes into equations, interpret how equations "behave," and communicate their understanding to others. Attention to specific and special characteristics of ACD and their formal understanding will be a necessary step in making ACD-STEMM integration work as effectively as possible for improving any particular STEMM educational outcome.

In sum, melding ACD with STEMM is not a mere matter of presenting the two together, or using ACD more clearly to explain a STEMM concept to students; rather, such melding must have some recognizable and explicit basis in the type of ACD being used to deliver a lesson and an explicit utility for the emerging STEMM professional in terms of skills, knowledge, concepts, structures, processes, methods, problems or aesthetic criteria. Equally important, the development of ACD-STEMM–integrated programs must recognize that different STEMM professionals use different ACD for different reasons. There can be no "one-size-fits-all" approach to ACD-STEMM integration; integration must, in the end, be not only discipline-appropriate, but also personally relevant.

The Futility of Distinguishing Between Near and Far Transfer

Finally, we would like to make a very brief but important comment on the on-going debate about near and far transfer that has bedeviled many discussions of whether ACD can usefully be integrated into STEMM learning. In brief, the issue is often framed as whether skill and knowledge transfer can successfully be achieved pedagogically between disciplines as apparently disparate as, say, mathematics and poetry or music and biology, as it clearly can be between closely related areas such as still life drawing and industrial drawing (e.g., Hetland & Winner, 2004). We believe that the evidence we have compiled above makes the entire near-far issue moot. STEMM professionals can almost always point to specific ways in which their ACD and STEMM practices connect: these are the twelve types of bridges that we describe above. These bridges are capable of linking any two subjects or disciplines when properly and appropriately built. Whether near or far, the bridge creates a link that draws the subjects together – to use an analogy from Madeline L'Engle's *A Wrinkle in Time* (1963), a bridge is like a "tesseract" that folds space and time to bring together that which was previously separated. The "folds" that are bridged may be very "near" in terms of disciplinary knowledge and practice (e.g., still-life drawing and industrial drawing) or very "far," such as observing in a fine arts class and observing in a chemistry lab. The point is this: bridges are not crossed simply by having science students make art, or mathematicians play music, and hoping that some universal sense of unity somehow results, but by revealing very limited and precise functional commonalities in methods, skills, knowledge, structures, and processes through the recognition of common patterns, analogies, practices, etc. Thus, when the Dana Foundation produced as part of its neuroscience series a study on the effect of arts training on general cognition, the report did not demonstrate any effects on general cognition, but rather found much more limited but quite significant lasting benefits from visual arts, music, and dance for very specific skills such as improved observation, pattern recognition, geometrical thinking and memory (or retention) across the curriculum (Gazzaniga, 2008).

There is an important lesson to be gleaned both from what STEMM professionals themselves say about the utility of ACD for their professional work and from studies such as that by the Dana Foundation. The more specific we can be about what the bridges are between any particular ACD activity and any STEMM learning objective, the more useful ACD-STEMM integration will be. This is not a novel conclusion, but rather one that is completely consistent with the view of Perkins and Salomon (1988; 1992a; 1992b), Burton, et al. (2000) and Schwartz, et al. (2005) that any kind of trans-disciplinary transfer requires that the expected outcomes be defined through pedagogical connections that are well-defined. The converse is also true; the less explicit the "bridges" are, the more futile it will be to put ACD and STEMM teachers in the same classrooms. This conclusion will be validated by the studies evaluated in the next two parts of our review, which focus on each of the twelve ACD/STEMM bridges described above.

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