III. Review of Studies Demonstrating the Effectiveness of Integrating Arts, Music, Performing, Crafts and Design into Science, Technology, Engineering, Mathematics and Medical Education, Part 3: Statistically-Validated and Controlled Pedagogical Studies of Eleven ACD-Integration Strategies Utilized by STEMM Professionals and General Conclusions

Robert Root-Bernstein*, Department of Physiology, 567 Wilson Road, Room 2201, Michigan State University, East Lansing, MI 48824 USA; rootbern@msu.edu

Ania Pathak, Michigan State University Neuroscience Graduate Program, Giltner Hall, 293 Farm Lane Room 108, Michigan State University, East Lansing, MI 48824; and Michigan State University College of Osteopathic Medicine, East Fee Hall, 965 Fee Road; Room A136, East Lansing, MI 48824 USA; pathakan@msu.edu

Michele Root-Bernstein, 720 Gainsborough Drive, East Lansing, MI 48823 USA; rootber3@msu.edu

Abstract: This is Part 3 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. Part 1 outlined twelve ways in which STEMM professionals say they use ACD in their work and the evidence for the efficacy of doing so. Part 2 summarized pedagogical studies that tested whether ACD improve aspects of STEMM learning by specific means of the Root-Bernstein's "tools for thinking" typology. This third part of our study analyzes whether the remaining eleven ways that STEMM professionals utilize ACD professionally have similar pedagogical benefits. Using a wide variety of search methods and sources, we have attempted to find all studies that employed some type of control group along with some type of formal analysis of results. We found only a few dozen acceptable studies and conclude that most of the eleven ways that STEMM professionals have found ACD to be useful have not been tested in pedagogically sound ways. Attempts to utilize ACD as non-specific potentiators of cognition to improve IQ, general mathematics ability, professional success, etc. did not yield improvements. Good educational outcomes were found only when transfer was carefully planned in advance and specific means of enabling transfer from ACD to STEMM subjects were utilized in designing the pedagogy. We conclude that properly designed ACD-STEMM curricula can have clear benefits but that very few ACD-STEMM intersections have yet been properly tested, particularly for K-12 and informal STEMM education, where the impact might be expected to be greatest. There is a tremendous opportunity here for future studies and pedagogical innovations. Criteria for "gold standard" studies are suggested.

Introduction

In Part 1 of this tripartite paper, we provided evidence that there are twelve fundamental bridges which science, technology, engineering, mathematics and medical (STEMM) professionals have utilized to connect arts, crafts and design (ACD) thinking, methods and materials to their professional work. In Part 2, we reviewed the existing literature on pedagogical approaches to integrating ACD with STEMM education through the most commonly employed integration strategy, Bridge 1, which involves the process connections inherent in a set of 13 imaginative "tools for thinking." The remaining eleven Bridges enabling ACD-STEMM integration will be analyzed in terms of their pedagogical utility here in Part 3 of this essay. These include the use of ACD to provide novel materials, methods, principles, problems and structures for scientific investigation; practice with the creative process, problem-solving approaches, and applications of aesthetic principles; mnemonic aids and communication techniques and skills.

Methods

As in Part 2 of this study, we have used a wide range of methods, using key word searches on PubMed, Google, ProQuest, and JSTOR databases and following footnotes within the studies so acquired. We also asked knowledgeable colleagues (especially those involved with the Science Engineering Arts Design [SEAD] Network) to provide sources. Our major criterion for including sources in this review was that they have some sort of control that provides a basis for statistical analysis of the results. In general, studies that we have included here are of one of the following three types: 1) studies in which there was a statistically significant difference in a STEMM outcome correlated with whether participants had *prior* ACD training of some kind; 2) studies in which one STEMM group was provided with ACD training and another was not; 3) studies in which different STEMM groups were provided with different types of ACD (or unrelated) training and the effects of the different interventions on STEMM outcomes were measured. Where appropriate, we have also included groups of controlled studies in which the ACD is only indirectly implicated in the STEMM outcome (see Part 2 of this essay. In general, we have not included pre-post test studies in which a single group is given a test or survey at the beginning of a pedagogical intervention and re-tested or surveyed again after the intervention—absent further evidence there is no way to know whether the specific intervention could have been replaced with any number of other interventions with the same result.

Overall, studies that provide different ACD (or unrelated) training to comparable groups and measure STEMM outcomes are the most reliable of the types of studies we summarize, and are certainly more so than ones that involve an ACD intervention compared with no intervention. We found no double-blinded studies (a virtual impossibility in an educational setting since the teacher, unlike a pharmacist in a pharmaceutical study, is inseparable from the intervention). Nor did we find cross-over studies (which would not make sense, since any lesson learned would presumable persist, unlike in a pharmaceutical study, after the cross-over). Correlation studies are the weakest in terms of drawing reliable conclusions regarding the impact of ACD on STEMM performance, but such studies are often the only data currently available. They, as well as the studies that indirectly link ACD training through thinking tools to improved STEMM outcomes, provide the basis for future, better designed and controlled studies.

As will quickly become apparent, huge gaps exist in our knowledge of whether the eleven bridges enabling ACD-STEMM interactions that we survey here can be employed in pedagogically useful ways. It is hoped that this study will provide the evidential and methodological case that these gaps are well-worth filling and encourage new and better studies in the future. For this reason, we have sometimes noted where very intriguing, but improperly controlled studies have been performed that might benefit from being revisited with proper controls.

Results

- **Bridge 2. Experience with materials, tools and methods of using them that may then inform STEMM practices.** Innovative experimental scientists and engineers differ from their less inventive colleagues in having significantly more experience with crafts that introduce them to materials, their properties, and the tools and methods required to work with them (Taylor, 1963; Saunders, 1963; Rossmann, 1964; Root-Bernstein, et al., 2013; Lamore, et al., 2013). For example, Martin Perl, winner of the Nobel Prize (Physics, 1995) reports, "The skills and knowledge I acquired at the Polytechnic Institute have been crucial in all my experimental work:

the use of strength of materials principles in equipment design, machine shop practice, engineering drawing…metallurgy….” (Perl, 2014). Nobel laureate Richard Smalley (Chemistry, 1996) also credits craft experience—in this case, in childhood—with honing critical skills:

> From my father I learned to build things, to take them apart, and to fix mechanical and electrical equipment in general. I spent vast hours in a woodworking shop he maintained in the basement of our house, building gadgets, working both with my father and alone, often late into the night. My mother taught me mechanical drawing so that I could be more systematic in my design work, and I continued in drafting classes throughout my 4 years in high school. This play with building, fixing, and designing was my favorite activity throughout my childhood, and was a wonderful preparation for my later career as an experimentalist working on the frontiers of chemistry and physics. (Smalley, 2014).

A search through the Nobel Prize website (http://www.nobelprize.org) for similar stories about crafts experiences reveals that dozens of other Nobel laureates recount similar experiences. Unfortunately, there appears to be no pedagogical research whatsoever into the use of arts and crafts to develop and understanding of material properties or to develop associated expertise with tools and methods related to invention and construction – a possibly grave oversight if the object of STEMM education is to train future innovators.

Bridge 3. Artistic techniques and phenomena previously unknown to STEMM professionals. The artist Adelbert Ames invented one of the most interesting perceptual phenomena to puzzle psychologists in many years. By building a shape-distorted room and permitting the viewer to observe it only through a single aperture, it was possible to trick the viewer into thinking that two equal-sized people were as much as two or three times different in height. This “Ames Room” became a standard apparatus for perceptual studies (http://www.bobolinkbooks.com/Ames/ChairDemo.html). Gestalt imagery, Rorschach cards, and many other types of perceptual studies have been developed from the discoveries of artists, while Marcel Duchamp’s “Rotoreliefs,” (Sekuler & Levinson, 1977), Op Art, “impossible figures,” and other artistic inventions have also contributed. Strangely, despite the huge impact of the arts on perceptual studies, and despite the use of artists’ materials to illustrate many STEMM textbooks, there appears to have been no systematic pedagogical investigation of artistic innovations as sources of STEMM insights, nor any systematic attempt to use these connections as a means to introduce STEMM students to these insights. Two valuable sources for development of such pedagogical materials exist, however: the journal Leonardo (http://www.leonardo.info/) and the journal Art and Perception (http://www.brill.com/publications/journals/art-perception)

- **Bridge 4. Novel artistic principles and structures that reveal new aspects of natural processes.** A considerable number of artists and designer take out patents on their inventions, and novel structures and principles of construction represent a significant proportion of these inventions. As in the case of artistic techniques and phenomena, these principles and structures can provide valuable insights for STEMM professionals, yet are rarely, if ever, explored systematically or used for teaching purposes. A particularly fecund example is Buckminster Fuller's invention of geodesic forms and the elucidation of the principles underlying their construction and stability. Fuller's ideas directly inspired both the solution of spherical virus structures and the elucidation of the eponymous class of chemical compounds, "buckminsterfullerenes" (Taubes, 1991). Kenneth Snelson's invention of tensegrity structures has had an equivalent impact on engineering design and even cell biology (Ingber, 2003). There appear to be, however, no courses designed to introduce STEMM students to ACD structures or principles of construction and design. This is an area ripe for pedagogical exploration.

- **Bridge 5. Recognition of unsolved problems lying at the junctions of ACD and STEMM.** The invention of perspective drawing and its broader application to anamorphic transformations provide an excellent example of how problems lying at the junction of ACD and STEMM can simultaneously benefit both sets of disciplines (e.g., Collins, 1992). Once again, this ACD-STEMM intersection does not appear to have been mined for its pedagogical applications, a particularly striking oversight given the obvious ways in which its exploration could benefit education in both sets of disciplines simultaneously.

- **Bridge 6. Experience navigating the creative process more efficiently and cogently.** Some STEMM professionals have asserted that their practice of ACD helps prepare them to understand and utilize the creative process more effectively in their STEMM profession. For example, surgeon Pascal Vouhé has found that musicianship enhances surgery in many ways:

> Most of the qualities developed by musicians during performance, can be applied metaphorically to surgical practice:

> *Concentration*. Intense concentration is a basic requirement for both musical performance and difficult surgical procedures.
>
> *Strictness*. A strict respect of the musical score is obviously mandatory. Similarly, the steps of a surgical procedure must be followed strictly to provide a satisfactory outcome.
>
> *Anticipation.* A musician is reading the score many bars in advance of what he or she is playing. A surgeon should also prepare subsequent surgical steps well in advance.
>
> *Improvisation*. Improvisation is the essence of jazz music. Even in classical music, there is place for some improvisation called rubato; this makes the expressive differences in interpretation between several performers. Improvisation in surgery is necessary to take care of any unexpected operative event.
>
> *Virtuosity*. Musical virtuosity includes several elements such as style, elegance, rhythm, spontaneity, rapidity or risk-taking. The same words can be used to define surgical virtuosity which makes a surgical operation safer and quicker.
>
> *Ability to listen.* A mandatory quality for a musician is the ability to listen to other musicians. In a surgical team, the surgeon should also be able to listen to the ideas and concerns of all the other team members.
>
> *Capacity to create harmony*. Harmony is the essence of musical performance. This a common experience that an efficient surgical team is constituted by a group of several people, physicians and nurses, working in harmony.
>
> I am convinced from personal experience, that developing those qualities inherent to musical practice and adapting them to surgery could improve surgical performance. (Vouhé, 2010)

In addition to the studies by Root-Bernstein (2003; 2009), Root-Bernstein, et al. (2008; 2013), Lamore, et al. (2013), and Niemi (2015) cited in Part 1 of this paper, two additional large-scale studies have generally validated Vouhé's proposition that practicing any creative activity in one's leisure time can improve one's professional creative potential. The first was a long-term analysis of thousands of Israelis from the time they underwent testing for mandatory military service at age eighteen until their mid-thirties. Milgram and her colleagues (Milgram, et al., 1997; Milgram and Livne, 2005; and Hong, et al., 1993) found that standard measures such as IQ, standardized test scores, and grades did not accurately predict career success, but that having an intensive, persistent avocation such as music, painting, photography, chess, etc. was highly predictive.

The second study involved 341 individuals in the United States whose leisure-time activities were analyzed in relation to various measures of openness and flexibility of thinking as well as job-related measures of performance (Eschleman, et al., 2014). As in Milgram's study, there was a very significant correlation between the amount of personal time spent on creative activities and high measures of job performance. These studies suggest that people learn valuable skills from their avocations that enhance understanding of how to perform well vocationally.

The closest thing to formal pedagogical study of whether or not training in creative process (or, perhaps, practice learning to learn) can have a positive impact on STEMM learning is a series of uncontrolled observations of the effects of integrating engineering and arts students into the same college design course. College students at the University of Georgia were organized into mixed engineer-arts groups that had to solve common design problems. Throughout the course, students were required to reflect deliberately on their creative practices and to share with each other their reflections. Results were analyzed in terms of the tools for thinking described at length in Part 2 of this essay. The investigators found significant qualitative changes in problem-raising and problem-solving skills among both groups over the semester. Students self-reported benefits not only to work in their major field, but also to their learning in general. In particular, engineering students were more likely to explore multiple possibilities and play with materials before settling on a presumably optimal approach than they were at the beginning of the course, while art students were more likely to employ logical thinking and optimization methods to formulate a preferred approach to their project. Students in both groups also became more likely to use more of the tools for thinking, and in more explicit ways, by the end of the course than they had at the beginning (Walther, et al., 2009; Walther, et al., 2010; Costantino, et al., 2010; Guyotte, et al., 2014; Sochacka, et al., 2016).

A similar course integrating art and engineering practices specifically designed to elucidate and elaborate the creative process was carried out with equal success by Fantauzzacoffin (2012). Both studies are quite promising and should be replicated for other ACD-STEMM combinations, but need to be validated by a randomly controlled study employing statistical methods. That said, the groups carrying out these studies explicitly addressed rationales for qualitative evaluation of learning outcomes that bear serious consideration in terms of what methodologies are most appropriate to pedagogical outcomes such as quality of work and thinking strategies (Walther, et al., 2010; Walther, et al., 2013).

- **Bridge 7. Practice in the application of transdisciplinary aesthetic principles.**

STEMM professionals often discuss the importance of aesthetics as criteria for the development and analysis of STEMM research and results (e.g., Tauber, 1997; Wechsler, 1978; Sinclair, et al., 2006; Silver & Metzger, 1989). Yet, the origins of their scientific aesthetic sensibility remain largely unexplored. In his biography of George von Békésy, Nobel Prize winner in Physiology or

Medicine in 1961, Floyd Ratliff made clear that Békésy's highly developed aesthetic sensibility in the realm of science was due to a purposeful, life-long devotion to music, visual and plastic arts. As Ratliff explained, "Békésy studied art not only for the great pleasure it gave him, but also for the effect that he believed it would have on his mind. Comparing one art object to another to determine quality and authenticity, he thought, greatly improved his ability to make judgments about the quality of scientific work, too" (Ratliff, 1976, 31-32).

Aesthetics in science is also given short shrift in the teaching of STEMM subjects (Mehta, et al., 2016), but on those rare occasions when it comes under review, case studies indicate that aesthetic sensibility and overt aesthetic training are effective STEMM teaching enhancers (e.g., Sinclair, 2004; Sinclair, 2006; Wickman, 2006; Jacobson & Wickman, 2008; Hadzigeorgiou, et al., 2015; Resnik, et al., 2000; Flannery, 1992; Flannery, 1993; Pugh & Girod, 2007; Zubrowski, 1982). Indeed, Picard, Papert, Resnick, Machover, Strohecker and their colleagues have argued that a re-introduction of the affective, sensual aspects of science is an absolute necessity for making pedagogical progress (Picard, et al., 2004).

Despite such acknowledgement, once again there appear to be very few formal controlled pedagogical studies of whether training in ACD-related aesthetic principles and concerns carries over, as von Békésy thought they did, to a better understanding of, or ability to implement, STEMM-related aesthetic criteria. One notable exception is a study by Girod, et al. (2010). Elementary school children were taught three standard science lessons, either in a typical, objectivist manner or in a manner specifically modified to explore and elicit from students the aesthetic qualities of the material being learned through attention to its artistic and sensual aspects:

> Tests of conceptual understanding before, after, and one month after instruction reveal teaching for transformative, aesthetic experience fosters more, and more enduring, learning of science concepts. Investigations of transfer also suggest students learning for transformative, aesthetic experiences learn to see the world differently and find more interest and excitement in the world outside of school. (Girod, et al., 2010)

Beyond this type of examination, there is even greater need to study whether STEMM teachers trained in ACD aesthetics can better implement scientific aesthetic considerations into their STEMM teaching, and whether students trained in ACD aesthetics are more likely to be able to recognize and use such aesthetics in STEMM learning, as well.

- **Bridge 8. Strategies for exploring and mastering new material efficiently.** Nobel laureate Robert B. Laughlin (Physics, 1998) says that music lessons and practice helped him learn how to learn:

> It was impressed upon me that there was such a thing as good study habits and that I would have to acquire them if I wanted to be a scholar. My mother also had us take piano lessons, and this had a similar effect. I hated those lessons, but I now play regularly for pleasure and have even tried my hand at composing. So mothers everywhere take heart. The indoctrination you administer now may have unanticipated positive effects years later. (Laughlin, 2014).

The possibility that ACD develop efficient learning strategies has been explored by Franklin, et al (2008). Franklin's team investigated the effects of musical training in college students asked to remember long lists of words. Students with many years of music training significantly out-performed students without any musical training. This effect disappeared, however, when the musically-trained students were prevented from rehearsing the lists of words. Then, both groups performed equally. Franklin et al. conclude that musically-trained students acquire strategies and habits (such as repetition or rehearsal) for learning and retaining information that are more effective than those employed by untrained students. This improved "executive function" may explain the many other studies demonstrating that students who participate in music or other arts over extended periods of time tend to have higher grades and standardized test scores than students who do not (e.g., Schellenberg, 2004; Southgate & Roscigno, 2009; Benedek, et al., 2014). Whether the elements of improved learning strategies inherent in ACD practice can be identified and isolated for use in more generally effective teaching has yet to be explored.

- **Bridge 9. Mnemonic and other mental devices that increase acquisition and retention of learned material.** Most disciplines have verbal mnemonic devices that students use to master material they need to have available in rote memory (e.g., medical students and practitioners, reviewed in McDeavitt et al., 2014). In some instances, STEMM professionals have exploited the benefits of poetry and music to aid such mnemonic purposes since rhyme, rhythm, and meter help to organize complex material in more memorable ways than free-form note-taking and help, too, to limit error during recall (Bower & Bolton, 1969). Notable examples of science songs that embed complex and sometimes lengthy material include the *Biochemist's Songbook* (Baum, 1982), a compilation of all the major biochemical pathways set to various show tunes; Gilbert's (2006) "The Histone Song," about the function of histone proteins in controlling chromosomes; and Flansburgh and Linnell's (2009*) Here Comes Science*, an introduction to science concepts for grade school science students.

Unfortunately, very few rigorous studies of the use of musical mnemonics in STEMM education exist, though those that do are promising. For example, VanVoorhis (2002) found that students of statistics exposed to relevant jingles recalled terms and their meanings better on tests than students who were only provided written definitions. McCurdy, et al. (2008) found that some groups of students clearly benefited from songs related to food safety. Two other studies found that the majority of students enjoyed and found useful Gilbert's "Histone Song" (Crowther, 2006) and the majority of engineers taking a biology class found the biology songs useful as well (McLachlin, 2009). Unfortunately, neither of these studies was properly controlled.

In addition, Cirigliano (2013) has recently reviewed the literature on the use of musical mnemonic devices in medical training and found that while there are many music videos on YouTube that are used by medical students and teachers at quite high rates (some have more than 100,000 views), there appear to be no controlled studies demonstrating that such medical songs actually accomplish the goal of improving student learning or retention. Indeed, there are serious limitations to learning new words in the context of song. Both Racette and Peretz (2007) and Tamminen, et al. (2015) found that word acquisition was improved only if the song was already known to the student. Otherwise, the listener had two separate tasks to learn simultaneously, which interfered with both. Thus, as Crowther (2012) has concluded, there is a great deal of research needed to validate the utility of musical mnemonic devices for STEMM learning, not least of which is whether students would benefit more from learning STEMM-related songs provided to them or from making up their own lyrics to their own favorite songs.

The same questions pertain to other types of ACD-related activities used to help provide mnemonic benefits similar to those that appear to exist for songs. In the first part of this essay, we noted that some anatomy classes are successfully using body painting as a means of consolidating learning (Nicholson, et al., 2016; Bennett, 2014; Finn, et al., 2011; Op Den Akker, et al., 2002). In similar vein, the making of original digital videos of neurobiological concepts produced deeper conceptual learning and increased retention (Jarvinen & Jarvinen, 2012). Presumably, the creation of one's own audio-visual materials requires more intellectual effort than merely memorizing terms or remembering pictures. The pedagogical question then becomes one of where the trade-offs occur between shallower, more fleeting but greater amounts of learning fostered by standardized teaching methods and the deeper, more sustained learning of less material acquired through the time-consuming effort of making one's own media-based materials. Moreover, it appears that not all types of student-generated pictures or images function more effectively than teacher-provided images as a means of learning and retaining new information (Carrier, et al., 1983). Clearly, this is an area in which, once again, more research is needed.

- **Bridge 10. Practice translating, transforming and transferring concepts and practices among disciplines.** Some arts embody or instantiate scientific principles. The kinetic sculptures of George Rickey, Jean Tinguely, and Alexander Calder, for instance, employ basic physics principles to engineer artistic ends. Bamberger studied the impact of having both teachers and students learn to make Calder mobiles in tandem with learning (or teaching) the basic physics of balancing weights on fulcrums. She found that both teachers and students fell into three groups: the first understood "intuitively" or "bodily" how to build mobiles, but could not explain what had been done in terms of the physical principles; the second could describe the physical principles and solve word problems using them but could not apply them in building a mobile; and the third could transform readily between building practices and physical theory (Bamberger, 1991).

The need to integrate theory and practice in order to develop complete understanding of subjects is clear from this study, as is the use of the arts to model STEMM principles. However, the observation that most teachers could not readily transform between theory and practice, nor synthesize the two activities into holistic understanding, must give us pause. Teachers incapable or ignorant of such integrated thinking may consciously or unconsciously inhibit students from learning the physical meaning of equations; transforming between words, equations, and graphs; or transposing problem-solving strategies from one set of problems to another, whether within or across disciplines. In this light, two explicit attempts to codify translating, transferring, and transforming concepts among and between disciplines to produce holistic understanding must be mentioned: Todd Siler's "metaphorming" approach described in *Think Like a Genius*

(2010/1996) and the Root-Bernsteins' "tools for thinking" approach described in *Sparks of Genius* (1999). Both approaches share many common features.

Siler defines metaphorming is a way of linking everything one knows to everything else, using analogies, metaphors, similarities, comparisons, contrasts, images, words, sounds, memories, imagination – "any and all means of connection making"! For example, start with something as simple as the following statement: "We need to cultivate the gardens of our minds" (Siler, 2010, 10). There is obviously a metaphor here – that our minds, like a garden, need to be planted and cared for if we expect to produce a beautiful crop of ideas. Transform the metaphor into a testable hypothesis: that as in gardening, the best results from cultivating the mind will come from acting with considered care from well-understood principles derived from well-controlled experiments.

Expand upon the mind-garden comparison by searching for other language that links thinking with cultivation: e.g., "her thoughts were layered like an onion." Use the onion as an analogy instead of a metaphor: the brain, too, is layered, and grows in a layered fashion. Understanding the ways in which the layers of the brain are formed (evolutionarily, embryologically, and psychologically) through time can help us improve the mind's product, which is thought.

Punning, too, is a valuable way metaphorming, so sticking with our botanical theme, one might suggest that we've wandered into a "mind field"! A field of minds shifts us from thinking about single minds to the ways in which minds interact, and many interactions in the physical world involve fields of a different sort: magnetic, electrical, gravitational. What are the equivalent "fields" by which human minds interact: language, art, music, mathematics, culture itself? Could equations be written for such "mind fields" by analogy to physical fields of force? And punning again, what of the obvious link to "mine fields" and the danger of over-doing a good thing?

The Root-Bernsteins' approach is similar to Siler's, but breaks down the "metaphorming" process into a set of discrete imaginative skills, i.e. the tools for thinking described in Part 2 of this essay. Transforming and synthesizing, the 12th and 13th tools in the imaginative toolbox, focus on the hows and whys of connection-making between disciplines, particularly as a "secondary step" in the overall creative process, when imaginative, personal knowledge must be articulated in forms communicable to others/

Both approaches to transforming concepts within and between disciplines have been taught to and used by STEMM teachers (e.g., Mishra, et al., 2016; Mishra, et al, 2011; DeSchryver, 2015a, b; Henriksen, et al., 2015). Unfortunately, there are no well-controlled studies demonstrating the effectiveness of either strategy *as a whole* in promoting ACD-STEMM integrated thinking—though efficacy has been demonstrated in the use of specific thinking tools employed in isolation to connect ACD with enhanced STEMM learning.

- **Bridge 11. Recreation (often involving re-creation) that stimulates new creation.**

According to his son, Hans, Albert Einstein knew firsthand the inspiritive powers of recreation: ''Whenever he [Einstein] felt that he had come to the end of the road or into a difficult situation in his work, he would take refuge in music, and that would usually resolve all his difficulties'' (cited in Clark, 1971, 106; see also Maja Einstein, cited in Sayen, 1985, 26). Indeed, Platt and Baker (1931) and Root-Bernstein, et al. (1993) found that half of all scientific insights occurred outside of work, many during leisure-time activities. Davis, et al. (2013) found further that patented inventions developed during leisure time turned out to be more valuable in terms of subsequent licensing rights than patented inventions developed during work time. And Eschleman, et al. (2014) documented across many disciplines that those employees who made "recovery time" a regular part of their work week (often by means of ACD-related avocations and hobbies) had higher work performance evaluations than those who did not. The implications for students and professionals working in STEMM fields is obvious: getting away from one's work can permit the mind to work in creative ways that brute force approaches do not.

Unfortunately, there are no pedagogical studies of whether STEMM students or professionals directly benefit by being trained, metaphorically speaking, "to go to their piano" or, as Banting did, "to take up their paintbrush" (Banting, 1979). This is a strategy crying out for formal investigation. Could purposeful free time actually increase learning?

- **Bridge 12. Recording and Communication**. As an example of ACD-STEMM

collaboration on recording and communication of data, we noted, in the first part of this essay, that there is widespread use of dance notations to record and display animal behavior and neurology data. It is, in fact, very common for STEMM professionals to enlist the aid of ACD professionals in order to better record and communicate their results. The longstanding collaboration between chemist George Whitesides of Harvard and MIT designer and photographer Felice Frankel is but one additional and notable example (Frankel, 2002; Frankel & Whitesides, 1997; Frankel & Whitesides, 2009; Frankel and DePace, 2012). There are many books on how to use design principles to produce better STEMM graphs and illustrations, for instance, the famous set by Edward Tufte (1983; 1990; 1997; 2006). Obviously, such recording and communication can and does benefit from the types of aesthetic considerations described above in our sixth pedagogical bridge for integrating ACD with STEMM content. It appears, however, that very little effort has gone into developing pedagogies that would improve STEMM student abilities in these data recording and communication through ACD exercises and lessons. In fact, the only well-controlled study that we found involved the use of role-playing exercises (a form of theater training) for medical students that significantly improved their patient interactions and ability to obtain and record data relevant to diagnoses (Windish, et al., 2005). We are left having to ask whether fairly obvious connections between ACD and STEMM learning demonstrably exist, such as whether students trained in visual arts make more effective graphs and understand their meaning more completely.

Outstanding Gaps with Special Emphasis on K-12 Education

Our survey reveals that the vast majority of well-controlled studies demonstrating a valuable link between ACD training and STEMM pedagogical outcomes involve either of two bridges: bridge 1, the use of imaginative thinking tools such as observing, imaging, patterning, modeling, etc.; and bridge 9, the use of ACD as mnemonic devices. As a result, many outstanding gaps will need to be addressed by future research. As noted above, there is little or no well-controlled evidence to support the use of ACD in STEMM education by means of bridge 2, experience with materials, tools and methods of using them that may then inform STEMM practices; bridge 3, techniques and phenomena previously unknown to STEMM professionals; bridge 4, novel principles and structures that reveal new aspects of natural processes; bridge 5, recognition of unsolved problems lying at the junctions of ACD and STEMM; bridge 6, experience navigating the creative process more efficiently and cogently; bridge 7, practice in the application of transdisciplinary aesthetic principles; bridge 8, strategies for exploring and mastering new material efficiently; bridge 10, practice translating, transforming and transferring concepts and practices between and among disciplines; bridge 11, recreation and relaxation to refresh the mind and prime it for illumination; and bridge 12, recording and communicating data.

In addition, there appear to be no well-controlled studies of ACD use in *informal* STEMM learning. This lack also raises the broader question of whether the integration of ACD into STEMM education might improve non-cognitive outcomes such as sustained interest, improved motivation, and curiosity for these fields. After all, the compelling purpose of many arts is to cultivate personal, sensory knowledge; intuitive, emotional intelligence; and aesthetic challenge to our presuppositions about the world—all of which pertain to lifelong and creative practice of STEMM disciplines.

Another gap calling for attention is the relative paucity of well-controlled ACD-STEMM studies involving K-12 pedagogy, where ACD-related training might be expected to have the greatest STEMM-learning impacts. The vast majority of ACD-STEMM studies are of college and professional pedagogy. Notable exceptions are the use of visual analogies for teaching complex scientific concepts to elementary school children (Glynn & Takahashi, 1998; Yanowitz, 2001); the use of artistic aesthetics to develop scientific aesthetics among elementary school students (Girod, et al., 2010); the two papers by Leopold and Leutner (2012; 2013) on the utility of student-generated visual or pictorial summaries of science content for acquisition and retention of knowledge among 10th graders; Groenendijk, et al.'s (2013) study on the use of design processes to link engineering and sculptural thinking among 9th graders; Uttal and Cohen's (2012) review of ACD interventions for improving visuo-spatial skills, the bibliography of which includes many K-12 studies; and Cromley, et al.'s (2013) study of different diagramming techniques as aids to STEMM learning and transfer in high school students.. In addition, Halpine (2004) carried out an uncontrolled, pre-post test evaluation of the impact of a combination of passive and active sculpture and drawing exercises on visualization and modeling facility, which demonstrated statistically significant impact only on 3rd and 4th graders, but the results will need to be confirmed with rigorous controls.

Two very well-defined and carefully controlled studies deserve special mention for their groundbreaking work and excellent methodologies. The first concerns the Framing Student Success project carried out in low income elementary schools in New York City as a way to improve math learning and literacy by means of visual arts lessons (Cunnington, et al., 2014). Students in several schools were randomized into different treatment groups, in which all possible permutations of the arts, literacy, and math teaching programs were explored. The art-math integration was based specifically on Perkins and Salomon's (1992a,b) principle that connections must be well-defined and appropriate to both the ACD and STEMM material being learned:

> [S]tudio project staff and artist/instructors [thus] sought to create a rich and thorough curriculum that encouraged students to see connections and construct analogies among subject areas…. Connections were made by emphasizing shared concepts and skills while maintaining consistent and appropriate emphasis on visual arts learning goals… [while] the math units explicitly reinforced and extended prior experiences with measuring, geometric reasoning, and other math skills and knowledge, emphasizing practical applications. (Cunnington, et al., 2014)

As the investigators noted, "The Framing Student Success project also provides an unusual example of lessons in which math skills were used to create art, in contrast with the more common practice of presenting art skills as subservient to other disciplines." The results were very consistent across classrooms and over several years, demonstrating that students integrating arts with math (in both directions!) performed much better on standardized math tests.

The second outstanding study of K-12 ACD-STEMM integration, and one that might be used as a gold standard for future studies, is analyzed in the paper by Ludwig, Marklein and Song (2016) concerning the effectiveness of the Wolf Trap Foundation for the Arts arts-integration program on pre-K and kindergarten math and science learning. Not only were the various interventions properly controlled with different groups of students receiving different types of pedagogy, but the ACD interventions were carefully integrated according to appropriately expected impact on particular aspects of STEMM learning.

As in the Framing Student Success project, each ACE-STEMM integration was individually devised to best utilize appropriately transferrable skills or knowledge. Unlike the Framing Student Success project, the Wolf Trap Foundation project utilized several ACD as needed to support different STEMM learning goals. For example, a dance exercise used simple choreography to develop skills in patterning and observing. Students were required to transform the movement of objects such as feathers and balls into their own movements and then to gather data from the choreographed moves that could be used in a graphing exercise. A theater exercise, in contrast, developed students' visuo-spatial skills by having them imagine a series of horizontal, vertical and symmetrical actions through space and time with a set of props and then having them act out those actions. Such STEMM-appropriate ACD activities were found significantly to improve student standardized testing outcomes.

Standards for Future Studies

In terms of setting up valid studies, we come to several conclusions. One is that the very best studies compare one ACD intervention with another or one ACD intervention with a non-ACD intervention. They do not compare an ACD intervention with absence of that intervention. The reasons for this are simple. There are a series of confounding effects that cannot be controlled for properly in the intervention-no-intervention model—or, indeed, in pre-post testing. These confounders include the Hawthorne effect (McCarney, et al., 2007), the Pygmalion effect (Mitchell & Daniels, 2003), and the placebo effect.

The Hawthorne effect describes the possibility that factors other than those being tested are actually at work in the changes observed in the subjects. The very fact that students are being taught and examined in a new and different way may cause them to perform better and this effect might occur regardless of the nature of the intervention. The Pygmalion effect is that higher expectations induced by the intervention on the part of either the teacher or the student or both lead to higher performance. And the placebo effect is that teachers might teach more enthusiastically and/or the students study harder or more effectively from the mere belief that an intervention will be effective. Finally, there is the well-documented novelty effect, in which *any* change that lowers the level of tedium or breaks with standard operating procedures will appear to increase learning. The novelty effect is, however, transient. Clark and Sugrue (1991), in a review of educational research, found that uncontrolled novelty effects cause on average 30% of a standard deviation (SD) rise (i.e. 50%–63% score rise), which decays to small level /a smaller level after 8 weeks.

Because of the confounding effects of novelty, false beliefs, higher expectations, and other hidden factors, it is particularly important that any study of ACD effectiveness in STEMM learning be properly controlled so that the outcomes are robust and reproducible. The importance of proper controls can be appreciated by comparing two recent studies of the impact of music lessons on mathematics ability among elementary school children. Yang, et al. (2014) performed a very well-controlled study of Chinese students who were well-matched for socio-economic factors, but differed in that one group had a year or more of music lessons while the other group did not. All students studied in the same classes in the same schools. Yang, et al. found that while there was a slight improvement among the language skills of those who received music lessons (probably due to improved auditory sensitivity), there was no improvement in mathematical ability or general academic performance. This is the outcome we would expect given the need to bridge specific ACD skill or knowledge acquisition with particular STEMM learning needs.

In contrast, Martinez has claimed to have produced very significant improvement in mathematics learning among disadvantaged children in California schools by means of music lessons (Martinez, et al., 2008). While the Martinez study appears to be well-controlled on the surface, dividing students in various classrooms randomly into various treatment groups, a detailed analysis reveals major flaws with their approach. In the first place, every student who received music lessons also received training in mathematics utilizing a new pedagogical approach. Control groups only consisted of music plus other types of lessons (e.g., in English language). In no case was the new mathematics pedagogy provided by itself or in conjunction with other treatments such as English language instead of music training. As a result, there is no way to separate out the effects of the musical training from the additional mathematical training. This is a controlled study, but not a well-controlled study!

Indeed, recent reviews of the effects of musical training on mathematical learning among K-12 students suggests that there is no reliable evidence of any tangible effect. The so-called "Mozart effect" does not exist when examined over reasonable periods of time with appropriate controls (Jaschke, et al., 2013; Mehr, et al., 2013). Simply giving students ACD training in a non-directed, uncritical manner has no STEMM benefits. This is not to suggest that music has no place in STEMM education—as the review provided above should make clear—but rather that any use of musical (or any other form of ACD) training *must explicitly connect* to a particular STEMM education need through one of the twelve bridges described in this tripartite essay.

As the previous example attests, our review of successful ACD-STEMM integration not only suggests what kinds of approaches are likely to work in the future, it also suggests approaches that should be avoided. We have not reviewed the numerous studies that demonstrate no effect of ACD integration into curricula, and will dip into that literature only briefly here to make the point that almost all of it ignores the longstanding advice of Perkins and Salomon (1992a,b; see also Burton, et al., 2006): skill and knowledge transfer can only proceed where the pedagogical reasons for integration are clearly defined and the methods appropriate for fostering the transfer.

Inoa, et al. (2014), for example, introduced theater arts accompanied by teacher development time for the English and mathematics teachers into four selected schools. Four student-matched schools were studied as controls, but received neither theater programs nor additional teacher development time. Like the Martinez, et al. (2005) study mentioned above, this study was not properly controlled, having two factors (theater programming and teacher development time) at work simultaneously, but failing to control for all of the permutations of those factors, and also failing to provide an alternative intervention to theater, such as art, music, or physical recreation. More importantly, the study also failed to state explicit ways in which the theater programming was expected to improve language arts and mathematics learning or to provide clear means for delivering and testing for such improvements. In consequence, the investigators were forced to admit that outcomes they qualitatively observed were inadequately supported or substantiated:

> The most notable limitation to this study was the lack of statistically significant results. Even though students who participated in ITAP often outperformed students in the comparison level subgroups by seemingly substantial margins, these differences were rarely statistically significant, possibly due to small sample sizes. Additionally, while teachers in the treatment group were provided with professional development opportunities throughout the study, no programmatic details are given besides amount of hours per year and no follow-up regarding the actual implementation of theater arts integration strategies in the language arts classroom is mentioned. Any possible influence of quality or regularity of arts instruction on outcomes was not considered in the data analysis that followed. (Inoa, et al., 2014)

The belief that simply “integrating” ACD professionals into school curricula, or even more specifically into science and mathematics classrooms, will improve general learning has led to many similar failures. A recent review of the impact of dance on science and mathematics learning by the National Dance Educators Organization (Bonbright, Bradley & Dooling, 2013) found only a handful (literally) of studies that reported positive results. None of these qualified as well-controlled according to any of the criteria employed here. This is not to say that dance may not have important benefits for kinesthetic learners (which include a disproportionate number of minority students [Bonbright, Bradley & Dooling, 2013]), but rather that any attempts to introduce dance into STEMM classrooms must, in future, define very clearly how dance activities are to be used educationally. In fact, this is exactly what Ludwig, Marklein and Song

(2016), mentioned above for outstanding methodology, did with great success, demonstrating that dance, when clearly appropriate to delivered STEMM material, was highly beneficial.

We can expand on this point with regard to visual literacy training as well. Visual literacy has been defined as “the ability of students both to interpret visual representations that are provided by instructors and also to create visual representations on their own” (Quillin & Thomas, 2015). Drawing is one of the most common and simplest-to-learn modes of creating one’s own visual representations and, as this tripartite essays attests, one with manifest benefits to STEMM students. Despite the evidence of its efficacy, however, drawing is rarely used in teaching STEMM subjects. A recent survey by Coleman, et al. (2011) found that only 6% of elementary school science teachers frequently asked their students to either draw something themselves or to label a drawing that was handed out to them. Seventy-three percent rarely or never did. If the benefits of drawing are so clear, why is it used so infrequently?

There appear to be two quite different reasons, one involving teachers themselves, the other involving the kinds of tests most often used to evaluate STEMM learning. Teachers teach what they are comfortable teaching. As one recent study concluded, “We teach who we are” (Henriksen & Mishra, 2015). Most STEMM teachers are not comfortable teaching drawing (or any other ACD) so, evidentially, they don’t. But we must excuse them for not doing so, because the tests that they have been taught (or commanded by governmental fiat) to give do not benefit from the types of learning fostered by ACD. A recent study accompanied by a review of the relevant literature on the efficacy of drawing for STEMM learning by Leopold, Leutner and associates (2012; 2013) concludes that elementary school students who were asked to create conceptual drawings of the science and engineering principles they were learning did no better on multiple choice tests than students who did not draw, but the students who drew fared very significantly better on tests of visualization, of interpretation of diagrams, and of transfer of their knowledge to other scientific problems.

Given that drawings can be provided to students by the teacher to be labeled, copied by the students, generated by the teacher in front of the students to incorporate student concepts, modeled by the teacher for the students, or generated by the students themselves, significant research remains to be done to determine which type of ACD intervention is most effective even beyond the bounds of multiple choice testing. Indeed, Tytler, et al. (2013) concluded from their own investigations into these issues that visual literacy as a classroom tool requires a great deal more articulation:

> [T]here was a need to clarify teacher understanding of the form, function and purpose of representational work in the classroom. While teachers recognized that students found work with representations engaging, and as offering insights into their learning, there was a need to consider (a) the sequencing of the use of representations and re-representations, and (b) the role of representations in developing student reasoning and understanding.

In short, we must once again insist that integrating ACD with STEMM education is not a matter of simply asking students to draw or model or dance some scientific observation or concept, but a much more complex undertaking in which teachers must be comfortable using the ACD they expect the students to use, and in which students must understand why they are being asked to use any particular ACD method to address a given STEMM need. We learn best when we know both how and why we learn what we learn.

And so we return, in conclusion, to a point made earlier in this tripartite essay about the ongoing debate over near and far transfer. The data summarized in the second and third parts strongly support our contention that the near-far transfer issue is moot. All effective transfer is "near" even when the disciplines are "far," the transfer being mediated by specific skills or methods or ways of thinking that form direct connections between the disciplines. ACD-STEMM integration must be made lesson plan by lesson plan to address specific learning needs. The very best integration is that in which the ACD practices are used to inform STEMM learning and STEMM practices to inform ACD learning. Such integration is not easily done well, but when done well eases learning!

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