II. Review of Studies Demonstrating the Effectiveness of Integrating Arts, Music, Performing, Crafts and Design into Science, Technology, Engineering, Mathematics and Medical Education, Part 2: Statistically-Validated and Controlled Pedagogical Studies of the Root-Bernsteins' "Tools for Thinking"

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Abstract: This is Part 2 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 summarizes pedagogical studies that test whether ACD improve aspects of STEMM learning in a specific one of these ways- the use of what the Root-Bernsteins have called "tools for thinking." These mental "tools" were previously identified in the book *Sparks of Genius* (Houghton Mifflin, 1999) as part of the creative problem-raising and problem-solving strategies shared by artists and scientists. These "tools" include: observing, imaging, abstracting, patterning, analogizing, dimensional thinking, modeling, empathizing and playacting, body thinking, playing, transforming and synthesizing. Studies reviewed here universally demonstrated one or more significant benefits from utilizing ACD as means to improve STEMM outcomes utilizing "tools for thinking" as intermediary "bridges" between the disciplines, but data is far more extensive for some "tools" (e.g., observing, imaging, modeling) than for others (e.g., abstracting, patterning, analogizing, body thinking, playing). Thus, important aspects of ACD-STEMM integration remain little studied and offer important avenues for future development. A similar analysis of the remaining eleven bridges which connect STEMM professionals to ACD (described in Part 1) will be provided in Part 3 of this essay.

Introduction

In the first part of this paper, we provided evidence that there are twelve fundamental bridges that 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 this second part of our paper, we will review 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 connectons inherent in "tools for thinking." The remaining eleven bridges enabling ACD-STEMM integration will be analyzed in terms of their pedagogical utility in the third part of this tripartite essay.

The concept of "tools for thinking" derives from study of the imaginative and creative processes of hundreds of people across many disciplines, though mostly from the arts and sciences (Root-Bernstein, 1989; Root-Bernstein, et al., 1993; Root-Bernstein & Root-Bernstein, 1999). The Root-Bernsteins identified thirteen imaginative skills or "thinking tools" that individuals at work in STEMM and ACD professions not only share in common, but often describe in nearly identical terms and employ in virtually identical ways. These tools include observing; imaging; abstracting; pattern recognition; pattern forming; analogizing; body thinking; empathizing and playacting; dimensional thinking; modeling; playing; transforming; and synthesizing. A survey of 225 mostly mid-career scientists and engineers undertaken as part of the research for two studies of ACD activities of STEMM professionals (Root-Bernstein, et al., 2013; Lamore, et al., 2013) revealed that all individuals used at least some of these tools and that all of the tools figured in the creative thinking of at least some STEMM professionals. A similar survey of 54 artists attending the National Art Education Association meeting in 2010 found that artists generally use a broader range of the thinking tools at higher rates than the scientists and engineers (See Table 1.) [These data have not previously been published.] Thus, there is reason to believe that practitioners of ACD may be good role models for training future STEMM professionals in the use of these tools for thinking. Since all thirteen thinking tools form useful links between STEMM and ACD for professionals in these disciplines (see Part 1 of this tripartite essay), we explore here whether these tools have been found to be *pedagogically useful* in ACD-STEMM integration.

Table: Thinking Tool Use by STEMM and ACD Professionals

"THINKING TOOL"	% SCI & ENG (N=225)	% ARTISTS (N=54)
Visual Observation	100	94.4
Tactile Observation	No Data	53.7
Aural Observation	No Data	55.6
Visual Imaging	93	74.5
Visual Images Expressed in Drawing	64.9	74.5
Tactile Imaging	14.9	54.5
Taste-Smell Imaging	15	25.5
Aural Imaging	41	40
Abstracting	51.2	81.5
Recognizing Patterns	100	94.4
Inventing New Patterns	No Data	66.7
Musical or Sound Patterns	18.2	40
ddAnalogies and Metaphors	74	75.9
Body Thinking: Emotions	18	87
Body Thinking: Kinesthetic	18	81.5
Body Thinking Expressed in Movement	13.4	40
Empathizing or Playacting	17.6	52.7
Physical Models	50.1	74.1
Mental Models	67.8	55.6
Exploratory Play	27.5	86.1
Transforming: Inventing Possible Worlds	53.8	81.8
Transforming: Thought Experiments	64.7	70.9
Synthesizing: Imagination	74	70.4
Synthesizing: Intuition	87.7	90.7
Synthesizing: Logic	89.6	79.6

Methods

In order to gather relevant studies, we have employed 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 references. 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 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.

We have also included groups of controlled studies in which the ACD is only indirectly implicated in the STEMM outcome. For example, there are many studies demonstrating that explicit training in various of the tools for thinking (such as observing or patterning or modeling) result in significant improvements in STEMM learning. Concomitantly, there are studies demonstrating that it is possible to teach the same tools utilizing ACD. In those cases where there are no studies utilizing the ACD as a means to improve STEMM learning directly, the ACD impact has to be inferred. We include these sets of studies because it stands to reason that if teaching a particular tool improves STEMM outcomes and ACD can teach that tool effectively, then ACD can in this case improve STEMM outcomes. Obviously, the actual impact of ACD on STEMM learning in such instance remains to be demonstrated properly. 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 is 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 thinking tools of bridge 1—or the eleven additional bridges enabling ACD-STEMM interactions that we survey in Part 3 of this essay—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.

Bridge 1: Results

OBSERVING. Observing can be defined as sustained attention to some phenomenon using any or all of one's senses (Root-Bernstein & Root-Bernstein, 1999). While every science textbook and every science curriculum of which we are aware advocates observing as a fundamental STEMM skill, there is a surprising paucity of well-controlled studies describing effective means to train observational skills. The one STEMM discipline in which the most pedagogical research on observing appears to have been done is medicine, where health care providers have a very limited amount of time to make observations critical to their diagnostic and treatment options.

Many studies have documented the fact that medical and nursing students general perform very poorly on visual observation tests, which has led to various arts-related interventions for training observational skills. In well-controlled studies, medical students, physicians, and nurses have all been shown to benefit in a statistically significant manner from courses designed to educate visual observing skills through the examination and analysis of paintings and drawings (Grossman, et al., 2014; Perry, et al., 2011; Klugman, et al., 2011; Naghshineh, et al., 2008; Kirklin, et al., 2007; Dolev, et al., 2001). Surprisingly, one quite obvious type of intervention that has not been subject to well-controlled study is having such students actually draw or paint objects themselves. Given the very common statements of late-nineteenth and early twentieth-century scientists that "that which has not been drawn has not been seen," this oversight is striking. It is also noteworthy that equivalent types of interventions have not, apparently, been attempted outside of the medical field where one could expect them to be equally efficacious and where art-science curricula have existed since the late nineteenth century (Jones, 1898; Mueller, 1935).

Aural observing can also be honed, particularly through musical training. Mangione and Nieman (1999; 1997) tested 868 medical students and interns for their ability to learn how to distinguish between and correctly identify stethoscope recordings of twelve different typical heart diseases. Those who could play a musical instrument were statistically significantly more likely to get the diagnoses correct. Given that the average physician is able to correctly diagnose only 19 percent of heart diseases using stethoscopy, and even cardiologists get only 23 percent of such diagnoses correct, there is clearly a desperate need to hone aural observation skills among medical professionals (Zoneraich & Spodick, 1995). Physicians and nurses also use aural observational skills when dealing with surgical and critical care equipment utilizing melodic alarm functions. It has been found that physicians and nurses who had previously played instruments are significantly better at discriminating between, correctly identifying, and responding to melodic medical equipment alarms used in surgery and critical care settings (Wee & Sanderson, 2008; Sanderson, et al. 2006). Once again, there appear to be no equivalent types of studies concerning the efficacy of music lessons for training the aural abilities of, for instance, field biologists to identify and distinguish the species they study or of mechanical engineers to correctly diagnose and identify the causes of various mechanical failures by sound.

Like visual observational skills, aural observation skills are trainable. The fact that healthcare professionals who have had music lessons exhibit demonstrably better aural observation skills than those who have not speaks indirectly to this issue. More apposite are two studies of nurses and nursing students demonstrating that music lessons are an effective means to remediate aural observational deficits. Pellico, et al. (2012) worked with a professional composer (T. C. Duffy of Yale University) to compose music with attributes appropriate for learning about heart sounds and rhythms. Advanced nursing students taking a 180-hour diagnostic course (much of it involving direct patient diagnosis and care) were randomized into two groups, one of which got an additional two-hour musical auditory training (MAT) session in which they learned how to attend to pitch, timbre, rhythm, and masking sounds within a complex musical environment. This single two-hour session resulted in the MAT-trained nurses performing significantly better in recognizing and correctly diagnosing a wide range of bowel, lung, and heart sounds ($p < 0.001$). (Study participants who did not receive the MAT training prior to the test were provided the training after the study was completed.)

A pilot study by Collins, et al. (2014) also suggests that a pair of 90-minute music lessons focusing on how to attend to rhythm, tempo, pattern, noise, and to remembering sounds (but not tied directly to medical sounds as in the Pellico, et al. study) had a similar effect. In short, auditory observational skill in STEMM contexts appears to be trainable through music. These results are consistent with other studies demonstrating that musicians are significantly better than non-musicians at speech-in-noise discrimination (Parbery-Clark, et al., 2009) and develop better aural working memory (Pallesen, et al., 2010), both of which are essential skills required not only for health professionals, but for STEMM professionals in many specialties.

IMAGING. Having observed accurately, STEMM professionals need to be able to recall and mentally manipulate their observations, a skill often called imaging. Imaging, like observing, can and often does employ any or all of one's sense (Root-Bernstein & Root-Bernstein, 1999). Imaging skills are highly correlated with multiple measures of success in STEMM subjects. Within imaging skills, spatial reasoning ability, which includes the ability to visualize objects in multiple dimensions and to imagine what they look like as they are rotated or moved, is of particular importance to STEMM students and professionals and has been demonstrated in every STEMM subject.

In the engineering field, Blade (1963) demonstrated that "the figural, or spatial, area of mental ability" appeared to be of far greater importance in predicting engineering ability than "verbal, reasoning, abstract mathematical and quantitative abilities… I believe that figural or spatial ability is related to the creative performance of engineering students" (p. 112; see also Blade & Watson, 1955). Similarly, engineer Eugene Ferguson (1977) argued that the work of the imaginative engineer is almost completely non-verbal and non-mathematical:

> "Much of the creative thought of the designers of our technological world is nonverbal, not easily reducible to words; its language is an object or a picture or a visual image in the mind. It is out of this kind of thinking that the clock, printing press, and snowmobile have arisen. Technologists, converting their nonverbal knowledge into objects directly (as when an artisan fashioned an American ax) or into drawings that have enabled others to build what was in their minds, have chosen the shape and many of the qualities of our man-made surroundings. This intellectual component of technology, which is non-literary and non-scientific, has been generally unnoticed because its origins lie in art and not in science. As the scientific component of knowledge in technology has increased markedly in the 19th and 20th centuries, the tendency has been to lose sight of the crucial part played by nonverbal knowledge in making the 'big' decisions of form, arrangement, and texture, that determine the parameters within which a system will operate." (p. 835; see also Ferguson, 1994)

Indeed, as one recent study argued, "Spatial reasoning accounts for 90% of the engineering research and design process" (Bertoline & Weibe, 2003). Another asserted that "eighty percent of the manufacturing gross national product passes through CAD, CAM, and CAE systems at some point. Every vehicle, aircraft, sophisticated electronics system, most industrial and manufacturing equipment, and most consumer products depend upon these tools" (Marks & Riley, 1995). In short, while not every engineering problem involves imaging, most do and engineers who lack facility with this skill are at a clear disadvantage.

The same disadvantages attend to students of medicine. Among medical students studying anatomy, those who performed the worst on a battery of visuo-spatial tests also performed the worst on practical tests of anatomical knowledge and dissection ability—though it must be noted that these same students did no worse than those with high visuo-spatial scores on non-spatial tasks and tests such as learning the names of nerves, bones, etc. (Rochford, 1985). Training in three-dimensional imaging improves surgical ability (Beermann, et al., 2010), suggesting that lack of visual ability is remediable.

Similarly, spatial reasoning skills and visual imaging ability have been tied by many studies to success in all types of science courses and mathematics. A comprehensive recent review of this literature has recently been carried out by Uttal and Cohen (2012), so it will not be duplicated here. Suffice it to say that students who do poorly on a variety of tests of visuo-spatial ability consistently perform poorly in their STEMM courses, while students who do well on such tests tend to perform much better. The striking thing about visuo-spatial ability is that, as James Mohler has written, "Most researchers agree that spatial ability is a trainable attribute" (Mohler, 2007; see also Tillotson, 1984; Alias, et al., 2002; Deno, 1995). Indeed, Uttal and Cohen provide dozens of well-controlled studies performed on students ranging from middle-school through graduate school demonstrating that visuo-spatial training intervention, devoid of STEMM content, nonetheless results in improved scores on a battery of generalized visuo-spatial skill tests and, at the same time, on various measures of STEMM learning such as classroom tests, standardized STEMM tests, persistence in major, and probability of graduating within a STEMM major. Uttal and Cohen particularly point to the work by Sorby as a model program (Sorby & Baartmans, 1996; 2000; Sorby, 2009a; 2009b).

The salient feature of visual thinking intervention studies is that no matter how visual imaging is taught, it has substantive benefits for STEMM learning outcomes: course material may involve specific visual thinking exercises, consist of learning computer-aided design, or focus on drawing, industrial drawing (or draughting), painting or sculpting, though drawing stimulates ideational fluency over use of computer-aided design programs (Uttal & Cohen, 2012; Ainsworth, et al., 2011; Halpine, 2004; Groenendijk, et al., 2013; Hinze, et al., 2013). Drawing, painting, and sculpting lessons may also improve spatial-kinesthetic imaging associated with engineering tasks such as designing robots (Vertisi, 2012).

Importantly enough, groups of students who typically underperform in STEMM subjects, such as women and some minorities, benefit the most from visuo-spatial training (Sorby & Baartmans, 1996; 2000; Sorby, 2009a; 2009b). Most of these studies involve ACD-related interventions that last months or years, but in some cases, even very short arts-related exercises can have a significant impact as the following study by Stericker and Levesconte (1982) attests:

> Eighty-three undergraduates [Ss] were pretested on 4 standard tests of visual–spatial skill, including the Group Embedded Figures Test and the Space Relations Test of the Differential Aptitude Tests. Half of the Ss were given 3 hrs of training relevant to the spatial tasks presented by 3 of the tests; all Ss were then posttested. The hypothesis that spatial "ability" is susceptible to practice and training effects was strongly supported. MANOVA showed that experimental Ss improved significantly more than controls, males and females improved equally and substantially, and training effects generalized to the untrained spatial task. The hypothesis that females score lower on spatial tests because they lack relevant practice was also supported; when female experimental Ss were compared with male controls on the posttests, the sex-related pretest difference favoring males was eliminated.

ABSTRACTING. Abstracting is the process of eliminating all unnecessary information from a set of observations to leave the essential elements or meaning (Root-Bernstein & Root-Bernstein, 1999). As such, abstracting is another critical skill used in a wide range of STEMM subjects (Root-Bernstein, 1989). Surprisingly, then, there has been very little empirical research into the uses of abstractions, as opposed to realistic representations of material, in learning STEMM subjects. The existing evidence suggests that realistic representation of material is favored over abstract representations if the object of a lesson is to identify the details of a specific object or process. If, however, the purpose of a lesson is to present a principle or process that is to be generalized across dissimilar sets of material or to diverse situations, then abstract representations are far more effective.

For example, Scheiter, et al. (2009) have demonstrated in a well-controlled study that material regarding cell mitosis was learned and generalized to other biological situations much better by training students with schematic diagrams of the process rather than photographs or video material of actual mitotic events. Similarly, Goldstone and Sakamoto (2003) found that students introduced to an abstracted, schematic version of strategies for food acquisition among ants were much better at transferring their understanding to other situations (e.g., other types of animal foraging) than those who observed actual ants foraging. Van Gendt and Verhagen (2001) observed the same outcome when teaching anatomy: students trained on photographs were better able to identify specific structures than students trained on abstracted line drawings, but the latter students were better able to generalize and apply their learning to other anatomical structures.

To provide additional examples, in another well-controlled study, Johnson, et al (2014) found that electrical engineering students learned circuit analysis principles much more effectively and transferably when the circuits were taught as abstractions rather than as realistic, contextualized images. Goldstone and Son (2005) also found that students who were introduced first to realistic protein models and then to abstractions of their basic structures were much more capable of generalizing their knowledge to new examples than those limited to manipulating realistic models. And, importantly, in well-controlled studies McDaniel and his colleagues found that students required to discover patterns in various types of data sets performed better, had higher retention of material and could extrapolate it better to new situations, if they abstracted out *their own rules* from the data sets rather than attempted to apply pre-taught rules to the data sets (McDaniel, et al., 2014; Little and McDaniel, 2015). (See also: Dwyer, 1968; Dwyer, 1976; Ferguson & Hegerty, 1995; Goldstone & Sakamoto, 2003; Johnson, et al., 2013; Johnson, et al., 2014.)

As with the other thinking tools described above, even in courses in which abstracting is a critical component, tests of abstracting ability at the outset of science and engineering courses do not predict class ranking at the end of term, suggesting that abstracting is a learnable skill (Bennedssen & Caspersen, 2008; Mostrom, et al., 2008). Unfortunately, this skill is rarely if ever explicitly taught in any STEMM curriculum, even in courses such as computer programming, where there is overt recognition of its importance (Koppelman, 2010). An additional problem with all of these studies, from the perspective of ACD-STEMM integration, is that *in no case has anyone taught students how to make their own abstract pictures or diagrams of the material that is to be learned!* With the exception of the McDaniel studies just cited, all extant studies of the importance of abstracting for generalizability and transfer of learning to new situations provide the abstracted information passively to the students. A clear need exists to determine whether students can be taught to abstract material for themselves and whether lessons in abstracting purveyed by means of ACD-based activities can be equally or more effective than teacher-provided materials.

PATTERNING. Patterning is another thinking tool for which ACD may provide some valuable skill development. Patterning involves both the recognition and the invention of organizing principles within a diverse set of elements. All hypotheses and theories in STEMM disciplines are explicit statements of patterns, thereby attesting to the importance of patterning to these disciplines. Pellico, et al. (2012) point out that observational skills are attendant on expectation and expectation in turn depends on the set of patterns with which one is familiar. Thus, part of observational training inevitably involves building up patterns of expectation through repetition and the memory (or image) of that pattern. Musical training clearly helps to develop pattern recognition and aural memory (i.e., aural imaging) concurrently with aural observation skills (Pellico, et al., 2012; Wee & Sanderson, 2008; Sanderson, et al., 2006). Shapiro, et al. (2006) found that medical students provided with 90-minute visual art and dance interventions weekly for six months had significantly improved pattern recognition skills compared with those viewing clinical photographs.

While it is well-understood that patterning is an essential component of learning all STEMM subjects (Harvard, nd; Hopkins, 1984; Silvia, 1977; Burton, 1982; Pasnak, et al., 1987), there is a stunning paucity of studies involving the explicit teaching of pattern recognition and pattern forming with regard to STEMM learning, whether by means of ACD or by direct teaching of these tools. One of the difficulties is that patterning requires the ability to abstract out a set of rules describing the salient qualities of the objects that form the pattern (McDaniel, et al., 2014; Little and McDaniel, 2015; Pasnak, et al., 2015), and abstracting, as we have just found above, is also slighted in most STEMM educational settings. It is nonetheless surprising to find that there are no well-controlled studies of the use of patterning in visual arts to develop patterning skills relevant to STEMM subjects.

ANALOGIZING. Analogizing involves the discovery and utilization of functional similarities between structurally different things. Though often confused with metaphors, analogies differ in an important way. On the one hand, metaphors generally involve the comparison of properties common to juxtaposed, often functionally disparate things, such as lips red as berries. Analogies, on the other hand, compare *functional processes shared by objects with dissimilar properties*. The moon falls like an apple from a tree; electrons vibrate like the strings of a violin. Readers will recognize in these assertions of functional similarity between unlike things the fundamental insights of Newton's theory of gravitation and of quantum physics.

As these examples must make clear, analogies provide STEMM professional useful links between solved and unsolved problems. One current example concerns the field of biomimicry, in which solutions to problems solved by evolutionary processes are examined as clues to ways to solve engineering problems in other fields. Another is the widespread use of M. C. Escher artwork to illustrate and teach different types of crystallographic forms of symmetry operations (e.g., MIT, 2015; e.g., Buseck, 2015; Orlov, et al., 2006). A notable product of such trans-disciplinary thinking is a design program called "Escher Sketch" that has been widely adopted by chemists. According to Chapuis and Shoeni (2015), "Since 1987, many crystallographers and many other specialists enjoyed the attractive software written for the Macintosh by Terry Flaherty from Loyola University in New Orleans. *Escher Sketch* was originally created for the purpose of designing periodic decorations. It was soon realized however that this application was an excellent teaching tool for the illustration of basic crystallography courses."

The use of Escher's artwork to teach crystallography has not, apparently, been the subject of formal pedagogical evaluation, so its popularity may or may not indicate efficacy. Nevertheless, it speaks to the wide use of analogizing in STEMM teaching. Harrison and Treagust (2006) have reviewed the many uses of both analogies and metaphors in STEMM pedagogy (as well as the dangers posed by inaccurate and misleading analogies!), but very few properly controlled studies of effectiveness exist. One notable exception is the study by Newby, et al. (1995) in which 161 college students receiving instruction in 10 physiological concepts were divided into three groups, one group being taught the concepts without analogies, the second group being taught the same material with the addition of a relevant analogy, and the third group receiving instruction with analogies along with additional instruction in how to best make use of these analogies. The students receiving instruction with analogies outperformed those without analogy training on both immediate test performance and long term retention of material, and those students receiving additional instruction on best use of analogies performed better than those who received analogy training without additional instruction (see also Stepich & Newby, 1988).

Baker and Lawson (2001) also found significant improvement in college student learning of genetics concepts in a group provided with complex analogies as compared with the group not provided with analogies. Very similarly-designed studies using elementary school children learning basic science concepts had virtually identical positive outcomes, with the greatest improvement in learning and retention occurring when the analogy was reinforced both textually and graphically (Glynn and Takahashi, 1998; Yanowitz, 2001).

One caveat in all of these studies is the recognition that analogies function best when they link what a student already knows to what needs to be learned (Harrison & Treagust, 2006) and are geared to the level of understanding of the student (Galesic & Garcia-Retamero, 2013). Whether ACD-related analogies might therefore be particularly effective in tying STEMM concepts into student experiences, especially for students with appropriate prior ACD training, has not been studied formally. Another glaring oversight is that there appears to be no research into whether student-generated analogies can be as effective as teacher-provided ones. Indeed, the studies reviewed above reveal that teachers very rarely ask students to generate their own analogies, which may be an area of great potential.

MODELING and DIMENSIONAL THINKING. Modeling involves making a simplified or miniaturized analog of a complex thing in order to test its properties. Dimensional thinking involves translating between dimensions in space and time. There is no STEMM subject that does not use modeling to think in very small or very large or very time-dilated ways. Despite this fact, very little research has been performed to investigate ways in which mental and physical modeling—or enhanced dimensional thinking—might improve STEMM education. Roberts, et al. (2005) and Bain, et al. (2006) demonstrated that the use of physical models in biochemistry courses not only significantly increased student learning outcomes, but also their understanding, appreciation and use of computer modeling software. Their results suggest that one effect of combining physical and computer models is to provide students with mediocre visualization skills practice converting between 3D and 2D representations of objects, without which the students fail to comprehend the nature of the 2D images.

Similar effects have been observed by Copolo and Hounshell (1995), Wu and Shah (2004) and Harris, et al., (2009). As Herman, et al. (2006) conclude, "Protein models function as "thinking tools" that stimulate discussion because the model itself provides spatial insights that stimulate questions and because participants can clearly articulate their questions in reference to the model." One might expect that physical models in general will provide STEMM students in all disciplines greater insights into the meaning and content of the 2D representations that they find on their computers and in their textbooks, not least by adding tactile and dynamic aspects to these models that may otherwise be lacking (Wu & Shah, 2004).

One notable aspect of modeling that is often overlooked is the necessity to transform between dimensions in making and interpreting models. The same skill is required properly to interpret two-dimensional diagrams of three-dimensional objects and to translate the essence of a three-dimensional object into a two-dimensional diagram. This ability is clearly related to visuo-spatial imaging ability (see above), which has been very well studied, but surprisingly the transformational aspects involved in dimensional thinking and modeling have almost completely been ignored. One noteworthy exception is the work of Müller-Stich, et al (2013), who demonstrated that the use of three-dimensional viewing technologies for training surgical students was far more effective than two-dimensional images, whether static or dynamic (see also Jurgaitis, et al., 2008). Be that as it may, training with three-dimensional viewing techniques did not improve the ability of radiology students to interpret two-dimensional CT scans, although it must be noted that in this particular case no practice in transforming between dimensions was included in the training (Metzler, et al., 2012).

Once again, as with so many of the previous thinking tools, the vast majority of existing studies testing the effectiveness of modeling for improved STEMM learning involve teacher-supplied models. Only one, uncontrolled attempt has been made to study whether student-made models might be even more effective than prepared models. This same study is the only one to explore whether modeling skills can be improved by arts-related modeling practices. The study in question was made by Gurnon, et al. (2013) and involved an integrated team of two artists (Julian Voss-Andreae, a former physicist, and Jacob Stanley) and a biochemist (Danial Gurnon). The faculty brought together art and biochemistry college students in a project to model protein folding through a series of student-designed and student-built artistic sculptures. All students were required to master the biochemistry of protein folding, electronic modeling software, craft techniques required to build the sculptures, and the aesthetic principles necessary to make these sculptures more than mere models. Students and teachers alike reported high levels of interest and participation leading to novel questions and increased facility with computer modeling software:

> For the science students who built the piece, the experience of fabricating the sculpture with their own hands provided a tactile insight into structures they were only accustomed to studying intellectually. Perhaps as a result, students developed an intuition for complex concepts of protein structure and folding. For example while constructing a wooden maquette of the most elongated backbone, students wondered whether a protein would begin folding as it emerges from the ribosome, and thus never truly resemble the

> completely unfolded structure they were building; in truth, the molecular dynamics simulation we employed begins with an artificially elongated molecule. On another occasion, walking alongside the row of completed structures, a first-year student asked if proteins fold by first crumpling inward and later adopting the recognizable patterns of a-helices and b-sheets—a question that is, in fact, still a matter of debate in the field. (Gurnon, 2013, 3)

If the results of this study are replicated by a better-controlled one, it could provide a very important benchmark for ACD-facilitated STEMM learning.

EMPATHIZING AND PLAYACTING. Empathizing refers to the ways and means of placing oneself in another's "shoes," experiencing the world from another point of view. Hay, et al. (2013) have noted that one of the least studied, but most important aspects of acquiring STEMM expertise is, in fact, that "the individual scientist gradually develops an embodied relationship with the phenomenal identities that constitute their object(s) of inquiry" (Knorr Cetina, 1999; Myers, 2008). Some part of this embodiment may involve kinesthetic, sensual and manipulative feelings associated with working with scientific materials (addressed below in body thinking). An equally important aspect of such embodiment is the ability of the STEMM expert to "become" the object of his or her study, to "playact" some part in the system that needs to be understood or engineered (Root-Bernstein & Root-Bernstein, 1999). The physical chemist and philosopher Michael Polanyi called this "personal knowledge," noting that subjective and idiosyncratic ways of "understanding" science often underpin creative work (Polanyi, 1962). Oxford zoologist Desmond Morris explains the imaginative process as he engaged in it:

> "With each animal I studied I *became* that animal. I tried to think like it, to feel like it. Instead of viewing the animal from a human standpoint—and making serious anthropomorphic errors in the process—I attempted, as a research ethologist, to put myself in the animal's place, so that *its* problems became *my* problems, and I read nothing into its life-style that was alien to its particular species" (Morris, 1980, 65).

Many other scientists have similarly "become" a whole range of animate and inanimate things, from subatomic particles to virus and plants to neutron stars as part of their research (Root-Bernstein, 1989; Root-Bernstein & Root-Bernstein, 1999).

No surprise, empathizing is a skill highly valued among medical practitioners and one that many lack. In consequence, a concerted effort has been made by many medical programs to teach empathy to healthcare providers. These programs often involve the reading of plays or poetry, the watching of performances about people suffering from various medical problems, or even the live enactment of patient-practitioner interactions by students themselves.

Unfortunately, the vast majority of such programs do not utilize reliable measures or instruments for measuring improvements in empathic ability. Stepien and Baernstein (2006) reviewed the available literature in 2006 and found only 13 studies utilizing reliable tests of empathy. Of these, only four involved a control group. Three of the four reported significant improvements in empathic ability among medical students, but the intervention in each case was explicit teaching of interview techniques. An additional five studies utilized theater or creative writing interventions and reported improved empathic ability among the students, but these studies were flawed by lack of controls or even lack of pre-post testing.

Nevertheless, such studies do suggest the plausibility of utilizing theater-acting techniques to improve empathic ability. For example, HeadSpace Theater (Ballon, et al., 2007) employs extremely clever role-playing improvisation games to teach medical students about the experiences of psychiatric patients, in which every student is assigned a role in a "play," but none of the roles are what they appear to be. In one exercise, the "doctor" discovers only during performance that everyone else in the room has been told he is actually a psychiatric patient who thinks he's a doctor, thereby experiencing quite unexpectedly what it is like to be treated as if "crazy"! Pre-post interview data from the HeadSpace programs indicate much more thorough and intensive learning in this program than in standard clinical teaching models (Ballon, et al., 2007). One suspects that if such a study were repeated with a proper control group and utilizing a standardized empathy-measuring instrument (Stepien & Baernstein, 2006), very significant results would emerge.

Outside of medicine empathizing and playacting are rarely examined and we found few studies that explored the use of ACD to improve STEMM learning by means of improved empathizing. The outstanding exception is Hay, et al.'s (2013) use of drawing in conjunction with empathizing to improve student learning of neurobiology. Three groups of participants were involved in the study: a group of expert neurobiologists (professors and active researchers), post-doctoral students, and undergraduate students. At the outset of the study, all three groups made drawings of neurons. Expert neurobiologists were readily able to identify the drawings of other experts and differentiate these from student drawings. Post-doctoral students had more difficulty making these distinctions, while undergraduate students were essentially unable to differentiate the expertise level of the artists. Indeed, undergraduate students tended to identify expertise in terms of how well a drawing matched the textbook images they were used to seeing (which are, in fact, often quite poor in terms of embodying expert knowledge).

Various interventions were then employed with the student group as they were learning about neurons, including the constant admonition, “Remember at all times that you are a neuron.” In other words, the teachers attempted to get the students to think about what they were learning in subjective, embodied terms. An analysis of the drawings made by the students after this intervention, and the ability of the students to identify expert drawings, demonstrated notable improvements, such that some of the undergraduate students were able to produce drawings indistinguishable from the experts themselves.

BODY THINKING: “For some scholars … sensori-motor experiences are at the heart of all our thinking” (Ke, et al., 2005, 1590; see also National Research Council, 2006). Kinesthetic awareness of body position, balance, and movement, of hand-eye coordination and gross motor control, as well as recalled images of body feeling and body movement, can all be employed as a kind of physical thinking that proves essential for experimental research and invention of all sorts. That said, manipulative skills and dexterity are not commensurate with or predicted by academic performance (Fadzil & Saat, 2014). While those students who excel at laboratory manipulations do not always do well in standard types of testing situations, students with great intellectual ability are not necessarily adept at laboratory manipulations either. Despite this gap, training in manipulative skills is generally short-changed in most STEMM curricula (Trowbridge, Bybee & Powell, 2000). Worse, standard approaches to teaching manipulative skills and dexterity within the STEMM curriculum are generally ineffective (Abrahams and Millar, 2008; Millar and Abrahams, 2009).

What formal studies there are have associated STEMM success, particularly in experimental sciences and engineering, with knowledge of and experience with tools. One of the few reliable correlates of engineering success in industrial settings is skill using tools that is developed prior to professional training (Taylor, 1963; Saunders, 1963; Rossmann, 1964). Sets of case studies by Ferguson (1977) and Hindle (1981) otherwise confirm the importance of arts for developing manipulative skills, as well as visual, tactile and kinesthetic observational ability (e.g., having a literal “feel” for how materials behave). Despite the manifest importance of manipulative skills for experimental scientists, however, the only studies that we could find of the impact of ACD on STEMM ability pertain to medical and dental professionals.

Most American dental schools require applicants to their programs to provide evidence that they have taken at least a year of some visual or plastic art, or a craft such as jewelry design that requires the manipulation of materials in three dimensions. A number of well-designed studies have demonstrated the utility of such requirements. Al-Jahony, et al. (2011) studied the relationship of drawing ability to manipulative skill and hand-eye coordination as related to dental skills using 71 second-year Arab dental students The study found that there was an excellent correlation ($p < 0.001$ by the cross-tabulation method) between both handwriting ability (determined from a written essay and measured by handwriting teachers) and drawing ability (copying a picture, as measured by professional art teachers) and dental skill (as measured by a class 1 amalgam cavity preparation). Similar results were obtained by Gillet, et al. (2002), who correlated the abilities of 45 French second-year dental students on pre-dental school standardized test scores, dental school written examinations, drawing ability, and dental practical skills (making fillings, crowns, etc.) assessment examination results. It was found that there were no significant correlations between any of the factors and the pre-dental school examination scores, but good correlations ($p < 0.01$ by ANOVA and Kruskal-Wallace tests) between measures of drawing ability and both dental school written work and the practical skills assessments.

Both studies confirmed previous studies relating manipulative ability on a variety of tests (such as bending wire to make a miniature sculpture or carving wax or plaster to match a pre-existing model or to match the dimensions indicated by a diagram) to dental skills such as making dental crowns or passing final practical skills tests (Glyn-Jones, 1979; Suddick, et al., 1982; Walcott, et al, 1986; Heintz et al., 2004). Shelton and Smithgall (2008) expanded the types of ACD activities to include, not just drawing, but music, additional visual arts, and various crafts such as mechanics and carpentry. They also found similar correlations between having broader ACD experience and better practical skills assessments among first year American dental students. Their data are unfortunately marred by providing no statistics.

Given the link that appears to exist between arts-trained manipulative dexterity and dental skills, it is not surprising to find a similar link between musical training and surgical skills--many types of musical instruments require the development of finger sensitivity and coordination. Boyd, et al. (2008) introduced a group of 30 medical students without previous training to laparascopic surgical procedures and found that those with no music training learned the techniques slowest; those who had played an instrument at some time in the past but were not currently practicing learned the techniques faster; and that those currently playing an instrument learned the techniques most quickly and efficiently. Harper, et al. (2007) reached the same conclusion in their study of 242 medical students learning robotic suturing and knot-tying techniques. Students who had been athletes or musicians were very significantly ($p < 0.01$) able to learn robotic surgical techniques much more quickly, and to make fewer errors while doing so, than those without such training.

Other crafts and hobbies did not provide any significant benefit in learning these robotic techniques. Students who reported significant time playing video games, which one might expect to prepare them for robotic procedures, actually did significantly worse than the musicians and athletes. Interestingly, no significant correlations have been found between any ACD and laparoscopic or orthopedic surgical skill among first year medical students, but video game playing is correlated with laparoscopic skill (Putnam, et al., 2014; Madan, et al., 2008). Harper, et al. (2007) note that laparoscopic manipulation and robotic manipulation differ significantly in terms of how the hands are used. Too, there is a greater need for 3D visualization in robotic surgery than in laparoscopic.

As with many of the previous tools for thinking, there is evidence that manipulative skills, hand-eye coordination, and related body-thinking skills are trainable, not innate. While trainability has not been demonstrated directly in STEMM subjects, many studies of medical and dental students have noted that, despite a strong correlation between tested manipulative or hand-eye coordination and ACD at the outset of dental or medical training, there is no evidence of such a correlation when the subjects are early-career professionals. Scores on the various medical and dental manipulation, sculpting, or drawing tests performed as part of the application process to professional schools, or performed during the first two years, have no predictive value for ascertaining which students will best master surgical or dental techniques, or be rated as passing the practical skills tests to graduate from medical or dental schools (Boyle and Santelli, 1985; Weinstein, et al., 1979; Gansky et al, 2004). These studies strongly suggest that while ACD give pre-health students an advantage with practical skills at the *outset* of their professional education, and enhance speed of learning, any deficit in ACD-related practical skills are eventually overcome by clinically-related practice.

TRANSFORMING AND SYNTHESIZING. Transforming and synthesizing, the last of the thirteen thinking tools deal with the integrated use of the entire tool box. One aspect of STEMM research and learning rarely taught explicitly is the necessity to transform data into hypotheses expressed through diagrams and models that synthesize multiple experiments and observations gathered using a variety of techniques. The desired outcome is a synthesis of sensations, feelings, impressions, information, theory, and experiments consolidated and expressed as coherent understanding. Seymour Papert described a similar concept with the term "syntonic learning," meaning learning that "is firmly related to children's sense and knowledge about their own bodies…. [and] is coherent with children's sense of themselves as people with intention, goals, desired, likes and dislikes" (1993, 63). Based on syntonic learning, his experiments in the use of "Turtle geometry" to teach basic mathematical concepts have often been cited as a major advance in mathematics teaching. Yet there appear to be no well-controlled studies actually demonstrating its effectiveness. A related development is "Aesthetic Computing," founded on an increasing collection of literature on the role of the body in learning, specifically in mathematics. Aesthetic computing therefore consists of methods for translating sensual understanding into a formal machine language (Fishwick, nd, 1).

STEMM educators well understand the need for transforming and synthesizing in learning and discovering processes such as reading a story from a picture and vice versa (Colburn, 2009) or devising and interpreting thought experiments from disparate sets of knowledge and then reformulating them as physical experiments (Galili, 2009). However, we found only two studies explicitly investigating transforming/synthesizing in a controlled manner. One was carried out on college students in a biology course by Jarvinen and Jarvinen (2012). Students were introduced to a section on neurotransmission by means of three approaches: 1) the "Conventional approach" (CA) (lecture and readings) (55 participants); 2) the "Powerpoint approach" (PPT), in which students added to CA a group-designed powerpoint presentation on the material they learned (155 participants); or 3) the "digital video approach" (VID), in which students added to CA a group-designed video presentation on the material they learned (27 participants). The efficacy of the three approaches was evaluated by means of a common final examination in which neurotransmission questions were designed to measure the "Remembering" and "Understanding" levels of Bloom's taxonomy of higher reasoning skills through both multiple choice and sketching diagrams. Data were analyzed using ANOVA and pairwise comparisons with Bonferroni correction. The VID group significantly outperformed the PPT group which, in turn, significantly outperformed the CA group on both remembering and understanding measures.

Of note, students benefited equally in each group whether they were, or were not, biology majors and the time required to create the powerpoint presentations was not significantly different than that required to perform the VID presentations. Improved learning outcomes were therefore independent of the amount of work performed by the students, suggesting that the nature of the extra work was what was most important for improving memory and understanding in both the PPT and VID groups. The single flaw in the study is that it appears that groupings were not made randomly but by individual student choice. It is therefore possible that VID students out-performed the rest because they were more highly motivated or had a higher level of STEMM learning prior to the interventions; additionally, CA students may simply have been the least motivated. Nonetheless, this study is well worth replicating in other STEMM contexts with the addition of randomized groupings.

A better-controlled study of the same sort was carried out by Cromley, et al. (2013) on high school biology students who explored learning and transfer outcomes associated with different methods of diagramming the material that they were learning.

> "Building on previous research showing positive results compared to control groups in both laboratory studies and short-term interventions, the authors developed three 6-week-long classroom treatments and compared their effectiveness in a sample of 137 high school biology students. Treatments involved students generating explanations (Self-Expl), completing a diagram with graphic elements (SCD-Visual), or completing a diagram with text (SCD-Verbal). Treatments were both effective for literal and inferential biology diagram comprehension, but the Self-Expl treatment showed greater pre-posttest gains on inferential items and SCD-Visual showed greater gains on literal items. Far transfer to geoscience diagram comprehension was only found for SCD-Verbal. There were no gains on biology knowledge for SCD-Visual. Analyses of instructional materials and students' coded answers during the intervention suggest that Self-Expl and SCD-Verbal conditions fostered more effort and more inferences while learning than did SCD-Visual." (Cromley, et al., 2013)

The Cromley, et al. study is particularly noteworthy in that it is clear that different types of learning (verbal, visual or combined) yielded different outcomes with regard to performance on different types of testing and in terms of transfer to other subjects. In other words, there is no single method of learning that is best in all situations. Visual learning may not benefit verbal testing while verbal learning may not aid in the identification and comprehension of visual or tactile materials. Transfer relates to what kinds of similarities exist between the different subject fields rather than the style in which the original material was learned. These are essential points to which we will return at the end of the third part of our essay.

Conclusions.

Despite the fact that STEMM and ACD professionals employ a common set of thinking tools (Table and Root-Bernstein, 1989; Root-Bernstein & Root-Bernstein, 1999), and despite the fact that many of these tools are recognized as required elements of STEMM curricula in many school systems, surprisingly little well-controlled pedagogical research has gone into investigating how best to make use of these trans-disciplinary connectors. Nonetheless, where these thinking tools have been employed appropriately to train specific STEMM-related skills through ACD-based practices, the results have been uniformly positive. We conclude that the tools for thinking approach to ACD-STEMM integration has promise and offers a very wide range of new and original possibilities for future pedagogical research. As we will see in Part 3 of this essay, other approaches to ACD-STEMM integration employed by STEMM professionals have been far less studied and will require significantly more effort to develop and justify.

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