Correlation between tools for thinking; arts, crafts, and design avocations; and scientific achievement among STEMM professionals

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Previous studies of science, technology, engineering, mathematics, and medical (STEMM) professionals have identified a common "mental toolkit" composed of 13 "tools for thinking" that STEMM professionals use in their problem raising and problem solving. The present research surveyed a convenience sample of 225 STEMM professionals to investigate whether these "thinking tools" are correlated with STEMM achievement measured variously as patents filed or licensed, companies founded, number of papers and books published, and copyrights assigned. Some mental skills such as modeling and playing are significantly correlated with patent filings and licenses, and others are correlated with different measures of STEMM achievement. Previous research has also demonstrated that some of these thinking tools, most notably visual thinking skills, can be taught through various arts, crafts, and design (ACD) practices, resulting in significant improvements in STEMM learning outcomes. The present research therefore investigates in the survey pool whether ACD are associated with the same measures of STEMM achievement as thinking tool use. Correlations exist between use of some thinking tools and particular ACD avocations: Modeling and playing are correlated with persistent crafts avocations such as metalworking, woodworking, and mechanics, which are, in turn, significantly correlated with patent production. Most survey participants were explicitly aware of the connections between their ACD avocations; their STEMM work; and the tools, skills, and knowledge derived from the former. We conclude that integrating ACD with STEMM content by means of tools for thinking may be an effective way to achieve improved STEMM learning outcomes.

art-science | STEAM | cognition | crafts | tools for thinking

What relationships exist between the creative thinking skills of science, technology, engineering, mathematics, and medical (STEMM) professionals; measures of their achievement; and the avocations they practice? Might avocations develop skills that improve STEMM ability and performance? Might the answers to such questions provide pedagogical guides for improved formal and informal STEMM education?

A broad and deep set of research suggests that adult avocations are associated with various measures of STEMM achievement. Generally, high achievers in all disciplines tend to develop interests more intensively than the average person (1–3) and to integrate them more coherently and completely (4–6). Within STEMM professions, the more avocations a scientist has, the greater the number of fundamental discoveries he or she makes across a broader range of subjects (7, 8). Arts avocations, photography, writing poetry, and practicing crafts such as woodworking and metalworking significantly correlated with production of high-impact papers and honors like the Nobel Prize or induction into the US National Academy of Sciences (9, 10). Total number of avocations also correlated with these measures of achievement. Other studies found that persistent practice of crafts and visual arts across a lifetime is correlated with filing and licensing patents among Michigan engineers and National Academy of Engineering members (11, 12). Arts avocations are associated with patents filed by members of the general public as well (13).

Various explanations have been proposed for correlations between arts, crafts, and design (ACD) avocations and STEMM achievement: Perhaps smart, talented people are simply good at many, unrelated things or successful people have more avocational time than less successful people; maybe people choose combinations of professions and avocations that utilize their preferred skills; or perhaps the practice of skills in one domain fosters their development and use in other domains. As exemplified by dozens of personal testimonials, many STEMM professionals explicitly recognize the utility of their ACD avocations for their STEMM work (6, 9–12, 14–16). Such self-awareness of transdisciplinary connections, while far from constituting proof that avocational skills influence professional ones, nonetheless suggests something more than random associations of talent.

STEMM professionals consistently draw strong links between their ACD skills and a mental "toolkit" of 13 nonverbal, body-based "tools for thinking" (6, 14, 17, 18). These thinking tools, commonly shared across the arts and sciences, include observing, imaging, abstracting, pattern recognition, pattern forming, analogizing, body or kinesthetic thinking, empathizing, dimensional thinking, modeling, playing, transforming (integrating a set of thinking tools in a serial fashion [e.g., using models to play with a phenomenon to yield patterns that can be visually displayed]), and synthesizing (integrating tools to get an overall "feel" for a system or subject so that one knows what one feels and feels what one knows). Few STEMM professionals use all 13 of these nonsymbolic thinking tools, but all use some subset (9, 18). A study of 38 male scientists found significant correlations between the range of thinking tools used by a scientist and measures of achievement, such as how many high-impact papers he or she published, and honors, such as a Nobel Prize or induction into

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the US National Academy of Sciences (9). The use of diverse forms of visual thinking and kinesthetic or body thinking was particularly associated with achievement measures in that study.

Limited research suggests that general, functional relationships may exist between avocations and the preferred use of certain nonverbal tools for thinking. In the study of 38 scientists just mentioned (9), significant correlations were found between practicing visual arts and the use of visual thinking tools, between musical avocations and visual thinking, and also between various arts and crafts and kinesthetic thinking. Primarily verbal thinkers tended to have writing avocations. Since certain combinations of ACD and of thinking tools each correlate separately with the same measure of STEMM achievement, these correlations suggest the possibility that the practice of various avocations may build useful thinking skills in STEMM professionals, or indicate a predilection to use those skills both professionally and in leisure activities.

Heretofore, the development and practice of nonverbal thinking tools and their relationship to measures of STEMM achievement have been poorly understood. Similarly, correlations between avocations and STEMM achievement measures have eluded clear interpretation. As a result, it has remained untested whether developing tools for thinking through formal pedagogies and/or informal avocations might benefit STEMM students. The present study attempts to remediate some of our ignorance by investigating the range and frequency of nonverbal tool use as well as ACD avocations among a convenience sample of 225 successful STEMM professionals with regard to various measures of professional achievement such as number of patents filed or licensed, number of companies founded, number of papers and books published, and number of copyrights filed. These data were supplemented by voluntary written responses to survey questions probing the respondent's personal views on the relationships between their avocations and STEMM work.

Methods

Subjects. A convenience sample of 225 STEMM professionals was administered a survey that gathered information about their use of various tools for thinking as described in the Introduction; number of patent applications, number of licensed patents, number of companies founded, number of papers published, number of books published, and number of copyrights filed; and their participation in ACD activities and avocations as children (to the age of 14 y), young adults (to the age of 25 y), and adults (older than 25 y). A fourth category captured those individuals who had persistent participation in an ACD avocation from childhood through adulthood. Self-reports were coded as is, with the following qualifications. All achievement measures were assessed as either having that measure or not (e.g., published or did not publish books, filed or did not file patents). Dichotomization was chosen so as to eliminate the otherwise inherent bias that would have resulted from the men in the study producing more of every measured output than the women. Dichotomization provides insight into whether individuals are inventive types or not, rather than how successful they are at inventing. The same reasoning was used for companies founded since the outcome we wanted to measure is not how many companies individuals founded but whether they are entrepreneurial or not. One exception was published papers, since most survey participants had at least one publication. Publications were divided, following the Pareto principle, into two categories, with those having the highest 20% of papers in one and the lowest 80% in the other. The same survey, minus the achievement outcome measures, was administered to a convenience sample of 54 ACD professionals (mostly college faculty) at several arts education conferences and colloquia at which the authors presented seminars. The purpose in having ACD professionals as a control group was twofold: One was that we were examining whether ACD-related thinking is of value to STEMM professionals such that it made sense to have an ACD control group, and, second, surveying ACD professionals provided information relevant to determining whether individuals whose profession involves ACD utilize tools for thinking similarly or differently from STEMM professionals.

The survey (*SI Appendix*) was approved by the Michigan State University Institutional Review Board. The STEMM professionals were solicited via email from the following populations: current members of the National Academy of Engineering, faculty members of the College of Engineering or the College of Natural Sciences of Michigan State University, scientists and engineers funded to develop start-up companies by the Michigan Economic Development Corporation, and midcareer graduates of the Honors College of Michigan State University who had majored in a STEMM subject. Response rates varied between 10% and 16%. The STEMM professionals and ACD groups differed in the proportions of men to women, with the STEMM group being 59% male and the ACD group being only 13% male. Women were, on average, 10 y younger in the STEMM group.

Statistics. A χ^2 analysis (https://graphpad.com/quickcalcs/chisquared1.cfm) was used to evaluate the probability that differences in the distributions of thinking tool use and ACD avocations were due to chance. Because multiple analyses were performed on each category, Bonferroni correction (www.quantitativeskills.com/sisa/calculations/bonfer.htm) was employed. Pearson's correlation coefficient (https://www.socscistatistics.com/tests/pearson/Default2.aspx) was used to explore possible correlations between thinking tool use and ACD avocations.

Results

Fig. 1 provides the results of the survey of 225 STEMM and 54 ACD professionals regarding their use of various tools for thinking as enumerated above. For participant convenience, the survey aimed to capture tool practice by offering a large range of terms familiar to professionals and laymen alike (e.g., "thought experiments" as a form of imaging, "intuition" and "imagination" for nonverbal cognition in general). The survey also sought to capture the use of language-based thinking (e.g., "verbalizations," "logic") to compare the incidence of symbolic and nonsymbolic forms of thinking. Every nonverbal thinking skill is used by some subset of STEMM and ACD professionals, including unusual ones such as tactile, smell, and taste imagery. Almost every STEMM professional reported the use of intuition, visual observation, visual imaging, and pattern recognition as well as more standard modes of thinking such as logic and verbalizations. Over half also utilized abstracting, mental modeling, physical modeling, thought experiments (as an alternative description of imaging and, given overall data, assumed to be primarily visual), and possible world invention (a form of transformational or synthetic thinking making use of any or all other thinking tools). Notably, STEMM professionals used only two mental tools at a significantly higher rate than did ACD professionals, and these were logic and (surprisingly) visual imaging. Conversely, ACD professionals used many other nonsymbolic thinking tools at significantly higher rates than their STEMM colleagues, most notably those associated with making physical models, abstracting, body or kinesthetic thinking, empathizing, and playing.

Because the ACD professionals were mainly women (87%), while women made up only 41% of the STEMM professionals surveyed, we also investigated whether disparities between the ACD tool use and STEMM tool use were due to gender. Male and female STEMM professionals do differ in their use of various cognitive skills. In this study, men were significantly more likely to report using physical and mental models and visual thought experiments than were women. In contrast, women reported using verbal and body forms of thinking significantly more frequently than men. However, the thinking tool use displayed by female STEMM professionals did not approximate that of (mainly female) ACD professionals (Fig. 1), suggesting the difference in male and female tool use among STEMM professionals may not be wholly gender-specific. Female ACD professionals appear to find success using a different overall spectrum of thinking tools than female STEMM professionals.

The male and female STEMM professionals in the study also differed in terms of the achievement data (Table 1). Men in the study were more likely than women to file patents, license patents, found companies, write published papers and books, or file copyrights. However, peak achievements, in terms of companies founded and papers written, were similar for both sexes, although women outperformed men in peak number of books written. No significant correlations appeared between numbers

THINKING TOOL	% STEMM N=225	% ACD N=54	Chi Sq P value	STEMM Men N=132	STEMM Women N=89	Chi Sq P value
Logic	90	79.6	0.006	87.1	92.1	0.7
Intuition	89.5	90.7	0.49	87.6	89.9	0.51
Verbalizations	64.2	51.9	0.016	52.3	75.3	<0.0001
Internal Words/Sounds	34.3	40	0.22	25.8	39.3	0.008
Sounds Out Loud	19.4	32.7	0.003	18.2	27	0.04
Visual Observation	98	94.4	0.09	97.7	98.3	0.98
Visual Imaging	93	94.4	0.67	95	91	0.16
Visual Images: Drawing	64.9	74.5	0.02	67.5	59.6	0.1
Tactile Imaging	14.9	54.5	<0.0001	12.9	10.1	0.32
Taste-Smell Imaging	15	25.5	0.02	9.8	11.2	0.75
Abstracting	51.2	81.5	<0.0001	56.1	43.8	0.016
Recognizing Patterns	99	94.4	0.04	99.3	98.7	0.98
Musical or Sound Patterns	19.7	40	<0.0001	18.2	23.6	0.16
Analogies and Metaphors	74	75.9	0.64	72.7	65.2	0.07
Body Thinking: Emotions	31.6	87	<0.0001	23.5	46.1	<0.0001
Body Thinking: Discomfort	18	81.5	<0.0001	11.4	21.3	0.014
Body Thinking: Movement	13.4	40	<0.0001	14.4	13.5	0.96
Empathizing or Playacting	17.6	52.7	<0.0001	15.9	20.2	0.32
Physical Models	50.1	74.1	<0.0001	56.8	42.7	0.005
Mental Models	67.8	55.6	0.02	74.2	58.4	0.0003
Exploratory Play	27.5	86.1	<0.0001	31.8	27	0.26
Possible Worlds	53.8	81.8	<0.0001	53.8	53.9	0.99
Thought Experiments	64.7	70.9	0.19	70.5	56.2	0.003
Synthesizing: Imagination	74	70.4	0.38	75	73	0.65

Fig. 1. Thinking tool use by STEMM and ACD professionals. Significant differences in thinking tool use are indicated by a black or gray background.

of papers, books, copyrights, patents filed or licensed, or companies founded (Pearson's correlation coefficient: $r < 0.2$), with three exceptions. A very weak correlation ($r = 0.2$) was found between number of patents filed and number of companies founded, and a stronger, although still weak, correlation was found between number of licensed patents and number of companies founded ($r = 0.36$). Inventors, in other words, were more likely than noninventors to be entrepreneurs as well, but the two talents were only sometimes coincident. Licensed patents were highly correlated with filing patents ($r = 0.85$), as would be expected. Thus, each of the achievement measures (save for the two patent-related ones) examines a significantly different aspect of STEMM work, and success in one is rarely associated with success in the others.

Fig. 2 illustrates how nonverbal thinking tools and language-based cognitive skills relate to the various measures of achievement employed in this study. Intuition, analogizing, and nonverbal forms of imagery did not differentiate between any achievement measures, and may therefore be assumed to be equally useful for all aspects of STEMM work. However, physical modeling, visual imaging, and playing each correlated with patent production; visual imaging and mental modeling correlated with founding companies; and use of abstracting and physical modeling correlated with high rates of peer-reviewed publications. Interestingly, the preferred use of verbal thinking was negatively correlated with producing patents, licenses, and, surprisingly, books and research papers. Logic also correlated negatively with the writing of books. While a preference for thinking in words may improve writing fluency (and as we will see below, it is associated with ACD avocations involving writing), it apparently does not improve ability to make the discoveries or inventions required to produce peer-reviewed contributions to STEMM professions.

Fig. 3 provides a more nuanced examination of the specific relationship of verbal and nonverbal thinking skills to patent production. Here, it can be seen again that modeling and playing are significantly associated with patent production, but so are a variety of measures of visual imaging such as static, dynamic, and 3D images, and the use of imagination more generally. Once again, the use of verbal thinking is a negative correlate of patent production, but even more pronounced is a negative correlation with various bodily kinesthetic types of thinking.

Table 1. Achievement outcomes of male and female STEMM professionals in this study

Achievement	Women, n = 89 % (no.) > 0	Women, n = 89 High no.	Men, n = 132 % (no.) > 0	Men, n = 132 High no.
Patents	20.2 (18)	9	48.5 (64)	122
Licensed	16.9 (15)	5	40.9 (54)	50
Companies	18.0 (16)	2	32.6 (43)	5
Papers	56.2 (50)	350	83.3 (110)	400
Books	29.2 (26)	25	50.8 (68)	10
Copyrights	22.5 (20)	50	50.8 (68)	100

Data are displayed as the percentage of respondents who produced a given achievement, followed (in parentheses) by the actual number who produced that achievement. "High no." is the highest number of patents, companies, papers, etc. recorded by an individual respondent in that category.

LOGIC	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	36.3	41.7	0.608
Licenses	29.9	41.7	0.237
Articles (80/20)	18.9	16.7	0.79
Books	39.3	66.7	0.01
Companies	27.4	25	0.806
Copyrights	11.9	23.1	0.248

ABSTRACTIONS	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	42.6	30.9	0.069
Licenses	35.7	26.4	0.132
Articles (80/20)	24.3	12.7	0.025
Books	42.6	41.8	0.904
Companies	28.7	25.5	0.585
Copyrights	13.8	11.8	0.722

INTUITION	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	37.1	35.7	0.891
Licenses	31	32.1	0.9
Articles(80/20)	18.3	21.4	0.689
Books	40.6	53.6	0.194
Companies	28.9	14.3	0.103
Copyrights	13.6	6.3	0.407

ANALOGIZING	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	38.2	33.8	0.531
Licenses	33.1	26.5	0.322
Articles (80/20)	21	13.2	0.168
Books	39.5	48.5	0.207
Companies	26.8	27.9	0.854
Copyrights	11.7	15.6	0.515

VISUAL IMAGING	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	41.1	24.6	0.026
Licenses	33.9	22.8	0.117
Articles (80/20)	21.4	10.5	0.068
Books	44.6	35.1	0.207
Companies	**32.1**	**12.3**	**0.004**
Copyrights	13.3	11.1	0.726

MENTAL MODELS	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	40.1	30.1	0.146
Licenses	33.6	26	0.254
Articles (80/20)	21.7	12.3	0.091
Books	39.5	47.9	0.228
Companies	31.6	17.8	0.03
Copyrights	16	6	0.08

VERBALIZATIONS	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	30.9	46.1	0.021
Licenses	25	40.4	0.014
Articles (80/20)	**11.8**	**29.2**	**0.001**
Books	**32.4**	**57.3**	**<0.0001**
Companies	27.9	25.8	0.729
Copyrights	9.4	18.3	0.103

PHYSICAL MODELS	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	**47.4**	**25.7**	**0.001**
Licenses	37.1	24.8	0.046
Articles (80/20)	**26.7**	**10.1**	**0.001**
Books	50	33.9	0.015
Companies	27.5	26.7	0.893
Copyrights	17.1	8.1	0.094

NON-VERBAL IMAGERY	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	41.1	33.1	0.21
Licenses	32.7	29.7	0.622
Articles (80/20)	21.5	16.1	0.3
Books	42.1	42.4	0.962
Companies	31.8	22.9	0.134
Copyrights	12.5	13.2	0.902

PLAYING	Use (%)	Do Not Use (%)	Chi Sq P val
Patents	**52.2**	**34.0**	**0.002**
Licenses	**44.8**	**25.3**	**0.004**
Articles (80/20)	22.4	17.1	0.351
Books	41.1	44.8	0.614
Companies	31.3	25.3	0.352
Copyrights	14.3	12.1	0.711

Fig. 2. Percentage of survey participants (n = 225) with achievement outcomes (e.g., patents) who used a particular thinking tool. Because 10 comparisons were made on the same data, a Bonferroni adjustment requires that the P value be 0.005 to be significant at a 0.05 confidence level. Data in white type against a dark background represent cases in which there is a significant negative correlation between the thinking tool being used and the achievement measure. Data in bold black against a gray background represent cases in which there is a significant positive correlation between the tool being used and the achievement measure.

We also examined whether there was any correlation between total number of nonverbal thinking tools used by a STEMM professional and measures of STEMM achievement, and found that there was not (r < 0.1 in all cases). STEMM professionals with broader ranges of cognitive skill are not obviously more productive in any of the ways measured here than those with smaller ranges.

The next question we asked was whether ACD avocations correlated with the measures of STEMM achievement employed here. First, we examined whether it mattered when an ACD avocation was taken up (in childhood, adolescence, or adulthood) and whether persistence of an avocation over a lifetime was a better correlate to thinking tool use or achievement factors than were isolated time segments. These time segments are themselves correlated: Childhood ACD predict young adult ACD (r = 0.64), young adult ACD predict mature ACD (r = 0.65), and childhood ACD are fair predictors of adult ACD (r = 0.4). We have previously demonstrated that about 50% of adults continue to engage in childhood ACD and the probability that an adult will take up new ACD not explored as a child drops to about 10% (11, 12). We used both adult and persistent avocations to analyze the ACD–achievement interactions that follow, but only show the persistent data since both provided very similar results.

Particular ACD avocations were found to correlate with particular achievement measures. The relation of patent filings to persistent ACD avocations is illustrated as a case study in Fig. 4. Five avocations correlate positively with patent production when examined both persistently and in an adult-only analysis; these are woodworking, metalworking, mechanics, electronics, and music composition. Printmaking and photography practiced persistently (but not solely as an adult) also correlated with patent production. Only fabric arts correlated negatively with patent production when examined both persistently and in adulthood, but this result may be an artifact of the women in the study filing significantly fewer patents than the men, while engaging in fabric arts avocations at higher levels. Of 89 women in

Thinking Tool	% No Patent	% with Patent	Chi Sq P value
Expected percent	63	37	
N=225	(n=142)	(n=83)	
Thought Experiments	59	41	0.22
Logic	64	36	0.78
Intuition	63	37	1
Imagination	59	41	0.22
Observing	63	37	1
Abstractions	57	43	0.05
Analogies	62	38	0.78
Imagery: Non-Verbal	59	41	0.22
Visual Static Images	59	41	0.22
Visual Dynamic Images	57	43	0.05
Visual Drawn	57	43	0.05
Imaging: Tactile Feelings	57	43	0.05
Imaging: Smell/taste	70	30	0.02
Physical Models	**53**	**47**	**0.0014**
Mental Models	60	40	0.34
Internal Sounds/Words	**76**	**24**	**<0.0001**
External by Voice	**77**	**23**	**<0.0001**
Verbalizations	69	31	0.06
Visualized Symbols	69	31	0.06
Musical/Sound Patterns	67	33	0.2
Movement Feelings	67	33	0.2
Bodily Tensions/Discomfort	**88**	**12**	**<0.0001**
Emotional Feelings	**73**	**27**	**0.001**
Movement	71	29	0.008
Possible worlds	62	38	0.89
Imagination	57	43	0.05
Playacting/ empathizing	67	33	0.2
Exploratory Play	**48**	**52**	**0.0003**

Fig. 3. Patent filing as a function of "thinking tool" use by STEMM survey participants. This analysis is the inverse of that shown in Fig. 2. Fig. 2 shows how many people with a patent (or other achievement) used a particular thinking tool. This figure examines how many people using a particular thinking tool had a patent. If a "tool" was used equally by those who had no patents and by those who did, then the expected ratio would be 63% to 37%. Significant deviations from the expected ratio are shaded, and the shading formalism is the same as in Fig. 2. Because 30 comparisons were made on the same data, a Bonferroni adjustment requires that the *P* value be 0.0015 to be significant at a 0.05 confidence level.

the study, only 18 (20%) had filed patents or declared inventions, while of the 132 men, 64 (49%) had filed patents (Table 1). The same phenomenon may account for the negative correlations between patent filings and avocations such as singing, dancing, and writing poetry or fiction. Note, however, that these avocations had no negative association with other outcomes such as writing papers or filing copyrights.

A similar analysis demonstrated that founding new companies was significantly correlated with printmaking and photography in both the persistent and adult-only analyses. Founding companies was again negatively correlated with fabric arts, but the same factors as in patents were once again in play: Only 16 out of 89 women (18%) founded companies as opposed to 45 of 132 men (32%). Once again, it is important to recognize that we are comparing degrees of production within a uniformly successful pool of individuals.

Only one significant positive correlation was found between ACD avocations and writing books, and that was having a sustained electronics hobby ($P = 0.007$). A mechanics avocation also correlated weakly with book writing ($P = 0.02$). One negative correlation was also found between writing books and writing poetry or fiction ($P < 0.0001$), suggesting that the skills required to write concentrated, brief pieces such as poetry are significantly different from conceiving larger discursive works. No specific ACD correlated significantly with writing high numbers of peer-reviewed STEMM papers or to copyrighting.

Calculating Pearson's correlation coefficient resulted in no significant correlations between total number of ACD avocations and any measure of STEMM achievement ($r < 0.1$ in all cases). More avocations provided neither benefit nor a detriment for STEMM professionals with regard to the achievement measures studied here.

Having established that various nonverbal tools for thinking are associated with certain achievement measures and that various ACD avocations are associated with some of the same achievement measures, the question arose as to whether significant correlations existed between various ACD avocational practices and tool use. Individual tools for thinking did not correlate significantly with any individual ACD ($r < 0.20$ in all cases after Bonferroni correction). However, the patent and company data reported above (Figs. 2–4) suggested that various groups of thinking tools might correlate significantly with various groups of ACD avocations, and this turned out to be the case. We limited our analysis of these groups to ones that appeared to be most likely to yield significant results and made no attempt to explore the myriad permutations possible.

Comparing the aggregate of woodworking, metalworking, and mechanics (which were all correlated with patent filings and licenses) with either modeling or playing (each of which was also correlated with patent filings and licenses) yielded $r = 0.72$ in each case. The Pearson's correlation coefficient for the aggregate of woodworking, metalworking, mechanics, electronics, and composing music versus the aggregate of visual thinking, modeling, and playing was $r = 0.63$, but visual thinking tools were only weakly correlated ($r = 0.39$) with the combination of printmaking, photography, film/video, woodworking, and metalworking; this correlation dropped to $r = 0.20$ if woodworking and metalworking were replaced with drawing and painting. Thus, it appears that working in three dimensions (woodworking, metalworking, and mechanics) is significantly better correlated in this group of scientists with unusually high use of visual thinking and modeling skills than are 2D forms of art such as drawing, painting, and printmaking.

In addition, use of verbal and body thinking skills grouped together compared with singing, dancing, fabric arts, and poetry or fiction writing grouped together resulted in $r = 0.91$. Verbal thinking alone correlates well ($r = 0.79$) with a combination of singing, dancing, fabric arts, and writing poetry or fiction, and body thinking correlates with the same ACD with $r = 0.71$. Breaking this correlation down, the correlation coefficient dropped to $r = 0.46$ for the use of internalized and externalized sounds/words, verbalizations, and internalized symbols versus the aggregate of singing, dancing, and acting. The use of body tensions, emotional feelings, body movement, and movement feelings correlated more poorly with singing, dancing, and acting, with $r = 0.41$. These results suggest that scientists who prefer verbal forms of thinking also prefer ACD associated with verbal skills, scientists who prefer body thinking also engaged more frequently in body-related ACD, and there is a significant correlation between verbal and body thinking skills.

Art/Craft	No Patent %	Patent %	Chi Sq	P value	No Company %	Company %	Chi Sq	P value
PERSISTENT AVOC	N=142	N=83			N=164	N=61		
Drawing	23.2	18.1	1.7	0.19	20.1	24.6	1.56	0.21
Painting	9.9	8.4	0.54	0.46	7.3	14.8	4.83	0.02
Sculpting	0.7	1.2	0.8	0.48	1.2	0	-	-
Pottery/Ceramics	4.8	0	-	-	3.5	1.8	2.04	0.15
Photography	**23.2**	**37.3**	**11.1**	**0.0009**	**25**	**37.7**	**9.01**	**0.002**
Print Making	**0.7**	**3.6**	**9.1**	**0.0026**	**0.6**	**4.9**	**16.16**	**0.0001**
Play Instrument	28.9	26.5	0.2	0.65	26.8	31.1	0.81	0.37
Composing Music	**1.4**	**8.4**	**49.5**	**0.0001**	3.7	4.9	0.48	0.49
Singing	**23.9**	**12.0**	**13.6**	**0.0002**	18.9	21.3	0.32	0.57
Dancing	12.0	2.4	9.5	0.0021	7.9	9.8	0.37	0.55
Acting	4.2	1.2	2.3	0.13	3.7	1.6	2.04	0.15
Film/Video	1.4	0	-	-	0.6	1.6	1.01	0.32
Magic	0.7	1.2	0.8	0.48	1.2	0	-	-
Woodwork	**12.0**	**27.7**	**12.7**	**0.0004**	17.1	19.7	0.64	0.42
Metal Work	**0.7**	**12.0**	**122.2**	**0.0001**	5.5	3.3	1.2	0.27
Mechanics	**4.9**	**19.3**	**41.3**	**0.0001**	11	8.2	1.04	0.31
Fabric Arts	23.2	10.8	14.7	0.0001	**22**	**9.8**	**16.01**	**0.0001**
Electronics	6.3	24.1	57.5	0.0001	11.6	16.4	2.84	0.9
Architecture	2.1	1.2	1.0	0.32	1.8	1.6	0.001	0.98
Poetry/Fiction	**19.7**	**7.2**	**22.1**	**0.0001**	14	18	2.7	0.1
Non-Fiction	20.4	21.7	0.23	0.63	18.9	26.2	2.68	0.1
Programming	12.0	19.3	4.6	0.03	12.8	19.7	4.33	0.037

Fig. 4. Correlations between persistent practice of arts and crafts avocations (AVOC) with patent filings and founding companies. Because 22 comparisons were made on the same data, a Bonferroni adjustment requires that the *P* value be 0.002 to be significant at a 0.05 confidence level. Shading formalism is the same as in Fig. 2.

Notably, some thinking tools and ACD appear to be negatively correlated. Pearson's $r = -0.63$ for the aggregate of woodworking, metalworking, mechanics, electronics, and composing music versus verbal and body thinking measures (internalized and externalized sounds/words, body tensions, and emotional feelings). So, just as one might infer from the patent and company data provided above, people preferring different mental skills also engage in significantly different ACD. These different preferences are also apparent in the types of scientific achievements they attain.

The free response comments to our survey reveal some of the types of relations that successful STEMM professionals perceive themselves. As previously reported, 65% of STEMM professionals surveyed stated that their avocation had some type of direct impact on their STEMM work and 82% expressed the opinion that ACD should be required as a formal part of STEMM education to develop relevant skills (11). Representative comments from individuals in the present study who had founded new scientific companies can be categorized roughly into five categories:

i) Skill transfer. STEMM professionals relate cognitive skills learned in ACD to their science practice:

> "It's handy to know how to use tools and manipulate materials."

> "One craft builds skills in others. So, if you know how to sew, those skills are transferable to other areas . . ."

> "[Crafts] make it easy to design hardware that can be built simply."

ii) Improved representation of data and ideas. STEMM professionals link imaging and visualizing skills learned in ACD to improved understanding of science:

> "Creativity, visualization, and drawing to support ideas and concepts"

> "Organic chemistry is very graphical in its nature. Drawing and imagining molecules is very important."

> "Physics and engineering require effective visual representation of data, understanding art and photography [is] an asset."

iii) Improved pattern analysis and problem solving. STEMM professionals report that abstracting and patterning skills learned in ACD benefit scientific practice:

> "The analytical skills learned in formal education are complemented by learning to deal with abstract concepts and creativity learned from designing and building furniture from wood."

> "I take advantage of my ability to draw as well as [my] eye for form and color to analyze and display data to bring out patterns from complex datasets."

> "I use art to explain and illustrate creative problem solving in science. I use and teach these concepts in a university and in the R&D lab."

iv) Improved facility with creative process. STEMM professionals connect ACD to exercise of creative behaviors and deeper understanding of creative process in science:

> "Woodworking taught planning, creativity, appreciation for natural products, functionality. Music taught creativity, perseverance, practice, attention to detail."

> "The ability to make things out of materials (such as sewing) allows me to devise creative solutions to experimental problems."

> "I think that everyone could and should find some type of arts and crafts outlet that is of interest to them. It teaches discipline, patience, and perseverance, along with providing an outlet to free think and problem solve. These are valuable life skills that can be applied in any profession, but especially in working with innovators."

> "It is a somewhat subtle link, but having learned a lot about the creative process helps in problem solving, envisioning solutions, working with people, and other skills."

v) Openness of mind and inspiration. STEMM professionals report that ACD stimulate curiosity and promote flexible exploration of STEMM subjects in ways not taught within the scientific method:

> "I think having a broad education, including arts education, is important regardless of vocation. Having an open mind and

eagerness to experience different media/perspectives/ideas through art leads to curiosity."

"I love science and art in the same way—the creativity in both are extremely important to me. I have my art studio adjacent to my science office and switch off and on between the two."

"My current occupation does not formally require any of my avocations, but my way of thinking and problem solving, of leading and guiding others is very much derived from my [avocational] experience."

Altogether, STEMM professionals in this study report that ACD reinforce STEMM practice in in a variety of ways, ranging from the exercise of specific tools for thinking such as visualizing, abstracting, and patterning to more transcendent aspects of the creative process itself. These STEMM professionals generally believe that cognitive skills exercised in the arts and crafts transfer to STEMM, improving the representation of data and ideas, enhancing pattern analysis and problem solving, deepening facility with creative process, and promoting creative behaviors such as curiosity and openness to the inspirations of a wider experience.

Discussion

Great care must be used in interpreting the data provided here. All participants in the survey were fully employed STEMM professionals, mostly (but not all) in midcareer. By this measure, all were successful. Unlike previous studies that examined differences between average scientists and high-achieving STEMM professionals as measured by numbers of high-impact papers and honors such as Nobel Prizes or membership in the National Academies or Royal Society (9, 10, 19), this study utilized criteria such as patents filed or licensed, companies founded, papers or books published, or copyrights granted to explore what skills may contribute to different ways of succeeding professionally.

This study provides a large-scale dataset addressing the diverse cognitive skills of working STEMM professionals, confirming anecdotal (6, 14) and smaller scale (9) studies concerning the breadth of their mental toolkit. The cognitive spectrum of STEMM professionals is quite broad, with over 50% using logic, intuition, visual observation, visual imaging, pattern recognizing, verbalizing, abstracting, mental modeling, physical modeling, devising thought experiments, or inventing possible worlds. This cognitive breadth among STEMM professionals is not generally recognized; neither is its overlap with other and different disciplines. The data provided in Fig. 1 demonstrate that STEMM and ACD professionals actually share a common set of nonverbal thinking tools as well as language- and symbol-based skills (14, 20, 21).

Some significant differences appear to exist between the tool preferences of male and female STEMM professionals in this study (with a higher percentage of men favoring modeling and visual thought experiments and a higher percentage of women favoring verbal and bodily kinesthetic thinking). With regard to visual and verbal abilities, these findings are similar to those of Nisbett et al. (22) and Hyde et al. (23), who argue that these particular gender differences in cognition are distinct, although generally small. We caution that expression of a preference for using particular thinking tools does not necessarily mean that individuals avoided using other thinking tools or failed to develop facility using them. Indeed, Hyde et al. (23), Uttal and Cohen (24), and Mohler (25) all point out that visual imaging ability, which is highly associated with STEMM ability, and in which women and minorities tend to test poorly, is a highly trainable skill and that training improves both visual imaging ability and a variety of STEMM learning outcomes. Evidence exists that the other thinking tools are also trainable and that such training also improves STEMM learning and success outcomes (18). Since all of our survey participants were successful STEMM professionals, it is possible, and indeed likely, that testing for ability to use these tools would show that most individuals have reasonable ability in most tools, but that does not mean that all individuals privilege the same set of mental tools in vocational and avocational settings. Thus, the meaning of gender differences in the use of visual imaging and modeling, verbal expression, and kinesthetic thinking that we have documented here remains open. What part of thinking tool use among STEMM individuals reflects gender, training, and/or professional socialization, and what part reflects idiosyncratic, stylistic choice? It is a limitation of this study that the question be recognized, but not answered.

Some differences in mentation did appear to matter in terms of the types of STEMM outputs individuals produced. The data summarized in Figs. 2 and 3 demonstrate that some sets of nonverbal thinking tools, particularly playing, physical and mental modeling, imagination, and visual imaging, were significantly associated with patenting and founding companies. In light of this finding, the fact that playing is used by only 27.5% of our STEMM professionals, and physical modeling is used by only 50%, suggests that some valuable cognitive skills might be underutilized by STEMM professionals generally and that training in their use might benefit inventing and innovating. It is again important to emphasize that significant evidence exists that training in mental tool use does improve both the ability to use that tool and a variety of STEMM learning and professional outcomes (18, 23–25).

The negative association of verbalizations and body or kinesthetic thinking with some of the achievement outcomes (Figs. 2 and 3) must be interpreted in context. In this study, female STEMM professionals utilized these thinking "tools" at significantly higher rates than male STEMM professionals (Fig. 1). Because the women were younger, on average, than the men and also filed fewer patents and founded fewer companies, it is possible that the negative associations are statistical artifacts reflecting the nonrandom distribution of the parameters being measured. Likely the gender differences discussed above are also at play here. Further research will be required to tease out what factors and correlations actually matter.

In addition to the correlation of certain thinking tools and STEMM achievement outcomes, some sets of ACD avocations correlated with these same achievement outcomes and with their associated thinking tools. In particular, various crafts, electronics, visual arts, and composing music correlated with patent filings, while photography and printmaking were associated with founding new companies. In turn, various groups of ACD correlated with use of various thinking tools, particularly the use of physical and mental models and playing. ACD involving 3D arts and crafts developed a different set of dimensional thinking skills than did 2D arts. Verbal thinkers tended to have writing-associated ACD avocations. Bodily kinesthetic thinkers tended to have movement-related avocations. These findings confirm and expand a previous, smaller study by Root-Bernstein et al. (9).

Persistent participation in various ACD from childhood through adulthood was the best correlate to the outcomes measured here, as well as to overall career eminence as measured in previous studies (11, 12), which raises the interesting possibility that, in the words of one of our anonymous reviewers, "a more general trait of persistence should be considered" to contribute to STEMM ability. Previous studies have, in fact, demonstrated that persistence is a key factor in STEMM success (e.g., refs. 26, 27), although it remains to be seen whether avocational ACD persistence is a useful predictor of persistence in STEMM studies and career development.

Survey participants expressed explicit awareness of the connections between ACD, thinking tool use, and the applications of both to their STEMM work, as has been documented anecdotally in previous studies (6, 9–12, 14–18). Such qualitative evidence helps limit the ways in which the correlational data provided in Figs. 2–4 can be interpreted. Recall that correlations between thinking tools, ACD avocations, and measures of STEMM achievement might be the result of high intelligence, general talent or ability, individuals choosing professions and avocations based on common favored skill sets, or mutual reinforcement of mental and physical skills common to both the profession and avocation. The fact that most of the STEMM professionals in this study were able to specify ways in which they used skills, processes, and knowledge acquired from their ACD avocations for their STEMM work, and that many of these involved an explicit recognition of common thinking tools and/or creative behaviors and processes, suggests, however, that there is something more than general intelligence or talent at work. Networking or integrating one's interests seems to be a characteristic of successful people (4–6).

An additional argument favoring ACD development or reinforcement of STEMM skills through thinking tool practice comes from well-controlled, randomized pedagogical experiments. Such experiments demonstrate that ACD can improve observing, imaging, abstracting, patterning, modeling, playing, transforming, and synthesizing skills and result in more effective learning and retention of material by STEMM majors, particularly in high school, college, and postgraduate courses (reviewed in ref. 18).

In sum, the research presented here provides a large-scale examination of the use of nonverbal tools for thinking among STEMM professionals, providing evidence that the range of cognitive skills used by these professionals is quite broad. Various subsets of these tools correlate with various measures of STEMM achievement; these same measures of STEMM achievement correlate with particular sets of ACD avocations; and these avocations, in turn, correlate with subsets of the thinking tools. While these correlational studies are open to many possible interpretations, ACD avocations likely help develop STEMM-related cognitive skill sets by improving the ability to use certain thinking tools. The existence of such a direct effect is supported by a combination of anecdotal evidence from written survey responses, along with evidence that the integration of ACD into STEMM classrooms to teach specific thinking tools improves STEMM learning and outcomes (18). Since some thinking tools proven to be of value in the current study, including abstracting, empathizing or playacting, modeling, and playing, are utilized at significantly lower rates by STEMM professionals than by ACD professionals (Fig. 1), these cognitive skills might benefit particularly from ACD-mediated pedagogical interventions (14, 18, 28).

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1. Cox CM (1926) *The Early Mental Traits of Three Hundred Geniuses* (Stanford Univ Press, Stanford, CA).
2. White RK (1931) The versatility of genius. *J Soc Psychol* 2:460–489.
3. Milgram RM, Hong E (1993) *Creative Thinking and Creative Performance in Adolescents as Predictors of Creative Attainments in Adults: A Follow-up Study After 18 Years. Beyond Terman: Longitudinal Studies in Contemporary Gifted Education*, eds Subotnik R, Arnold K (Ablex, Norwood, OH).
4. Dewey J (1934) *Art as Experience* (Minton, New York).
5. Gruber HE (1988) The evolving systems approach to creative work. *Creat Res J* 1: 27–51.
6. Root-Bernstein R (1989) *Discovering* (Harvard Univ Press, Cambridge, MA).
7. Cranefield PF (1966) The philosophical and cultural interests of the biophysics movement of 1847. *J Hist Med Allied Sci* 21:1–7.
8. Finklestein SN, Scott JR, Franke A (1981) Diversity as a contributor to innovative performance. *Biomedical Innovation*, ed Roberts EB (MIT Press, Cambridge, MA), pp 135–143.
9. Root-Bernstein R, Bernstein M, Garnier HW (1995) Correlations between avocations, scientific style, and professional impact of thirty-eight scientists of the Eiduson Study. *Creat Res J* 8:115–137.
10. Root-Bernstein R, et al. (2008) Arts foster achievement: Comparison of Nobel prizewinners, Royal Society, National Academy, and Sigma Xi members. *J Psychol Sci Tech* 1:51–63.
11. Root-Bernstein R, et al. (2013) Arts, crafts and STEM innovation: A network approach to understanding the creative knowledge economy. *Creative Communities: Art Works in Economic Development*, ed Rush M (National Endowment for the Arts and Brookings Institution, Washington, DC), pp 97–117.
12. LaMore R, et al. (2013) Arts and crafts: Critical to economic innovation. *Econ Dev Q* 27: 221–229.
13. Niemi L (2015) The arts & economic vitality. Relationships between the arts, entrepreneurship & innovation in the workplace. A working paper. Available at https://www.arts.gov/sites/default/files/Research-Art-Works-BostonCollege.pdf. Accessed December 31, 2018.
14. Root-Bernstein R, Root-Bernstein M (1999) *Sparks of Genius, The Thirteen Thinking Tools of the World's Most Creative People* (Houghton Mifflin, Boston).
15. Root-Bernstein RS (1987) Harmony and beauty in medical research. *J Mol Cell Cardiol* 19:1043–1051.
16. Root-Bernstein R (2001) Music, creativity, and scientific thinking. *Leonardo* 34:63–68.
17. Root-Bernstein R, Pathak A, Root-Bernstein M (2017) A review of studies demonstrating the effectiveness of integrating arts, music, performing, crafts and design into science, technology, engineering, mathematics and medical education, part 1: A taxonomy of integrated bridges. *Leonardo*, 10.1162/LEON_a_01579.
18. Root-Bernstein R, Pathak A, Root-Bernstein M (2017) Review of ACD-STEMM integration, part 2: Controlled studies of transdisciplinary tools-for-thinking bridges for arts-science pedagogy. *Leonardo*, 10.1162/LEON_a_01580.
19. Root-Bernstein R, Bernstein M, Schlichting HW (1993) Identification of scientists making long-term, high impact contributions, with notes on their methods of working. *Creat Res J* 6:329–343.
20. Root-Bernstein M, Root-Bernstein R (2005) Body thinking beyond dance: A tools for thinking approach. *Dance: Current Selected Research* 5:173–202.
21. Root-Bernstein M, Root-Bernstein R (2003) Martha Graham and the polymathic imagination: A case of multiple intelligences or universal tools for thinking? *Journal of Dance Education* 3:16–27.
22. Nisbett RE, et al. (2012) Intelligence: New findings and theoretical developments. *Am Psychol* 67:130–159.
23. Hyde JS, National Academy of Sciences (US); National Academy of Engineering (US); Institute of Medicine (US) Committee on Maximizing the Potential of Women in Academic Science and Engineering (2006) Women in science and mathematics: Gender similarities in abilities and sociocultural forces. *Biological, Social, and Organizational Components of Success for Women in Academic Science and Engineering* (National Academies Press, Washington, DC).
24. Uttal DH, Cohen CA (2012) Spatial thinking and STEM education: When, why, and how? *Psychology of Learning and Motivation*, ed Ross B (Academic, Oxford), Vol 57, pp 147–181.
25. Mohler JL (2007) An instructional strategy for pictorial drawing. *Journal of Industrial Teacher Education* 44:5–26.
26. Levin J, Wykoff JH (1995) Predictors of persistence and success in an engineering program. *NACADA J* 15:15–21.
27. Sithole A, et al. (2017) Student attraction, persistence and retention in STEM programs: Successes and continuing challenges. *Higher Educ Stud* 7:46–59.
28. Root-Bernstein R (2015) Arts and crafts as adjuncts to STEM education to foster creativity in gifted and talented students. *Asia Pac Educ Rev* 16:203–212.