This article presents the cognitive capacities and tendencies in the lives of computer scientists who play classical music as a serious avocation [1], following the general notion that mathematics/science and music are two manifestations of common ways of thinking [2–4]. The affinities between these two disciplines have been approached in the current research literature mostly through the presence of mathematical properties in music and through anecdotal evidence involving known personae and their innovations. This article offers a deeper look at the rather everyday lives of individuals who combine the disciplines of computer science and classical music in a work-avocation framework, in order to better understand how their concurrent involvement informs their ways of thinking. Framing this research as a phenomenological case study, narratives of seven study participants are constructed through open-ended interviews conducted in 2011, in which the participants relive their experiences of this phenomenon of embracing the two disciplines on a regular basis. Using qualitative research and thematic analysis methods [5], these narratives are analyzed to identify common cognitive abilities and tendencies, presented as four primary themes: being in the zone, assuming an engineering/scientific mindset, aesthetic thinking and joyous thinking. With such a rich thinking toolkit, this study motivates educators to support individuals with interdisciplinary interests and calls for such individuals not to leave behind their musical passions despite pragmatic career considerations.

THE MUSICIAN SCIENTIST—THE COMPOUND PUZZLE

The common notion that a significant proportion of mathematicians [6] and scientists have affinities for music, while not substantiated quantitatively, has been attributed largely to anecdotal evidence involving known scientist/musician personae and their innovations, and to the mathematical properties of music. R.S. Root-Bernstein and M.M. Root-Bernstein [7], through their analysis of the cognitive skills they believe are commonly shared by artists and scientists, provide names of such personae: physicist/violinist Einstein (1879–1955), chemist/doctor/composer Borodin (1833–1887), mathematician/composer Nevalinna (1895–1980), mathematician/composer Ansermet (1883–1969), cardiologist/composer Bing (1909–2010), mathematician/engineer Xenakis (1922–2001) and computer-scientist/composer Dabby (contemporary). The mathematical-oriented literature, on the other hand, explores the mathematical properties of music. For example, Fauvel, Flood and Wilson [8] describe uses of mathematics in acoustics by physician/physicist Helmholtz (1821–1894), in scale formation (e.g. Pythagorean scale [9]) and in composing music (e.g. Schoenberg’s [1874–1951] 12-tone system [10], Xenakis’s stochastic music [11]). Graves [12] expands on the presence of mathematical groups in music compositions [13], on electronic/computerized music and on the use of fractals [14] by composers/music-theorists Babbitt (1916–2011), Lewin (1933–2003) and Solomon (contemporary), respectively. Rothstein [15] explores the (conscious or unconscious) presence of mathematics in classical music compositions, such as those of Bach (1685–1750), Bartok (1881–1945), Beethoven (1770–1827) and Mozart (1756–1791). Pesic [16] describes music as a force in the development of modern science, Hofstadter [17] refracts Bach’s techniques through the mathematics of Gödel (1906–1978) and Chang [18] analyzes Beethoven and Mozart compositions for the purpose of practicing piano performance in a scientific manner.

Although both anecdotal and mathematical literature acknowledge the affinities between these two seemingly different disciplines of music and science/mathematics, it minimizes the voices and experiences of the people who...
live(d) in these two worlds, blends mathematicians with scientists and does not address the more contemporary math-based discipline of computer science. Driven by these perspectives, this article attempts to capture the voices of such people and present their ways of thinking.

**METHODOLOGY**

This study was framed as a phenomenological case study [19,20] of seven computer scientists [21,22] who have persisted with serious classical music-making. The desired subject profile included a minimum of 10 years of work experience as a computer scientist [23], a desired, although not required, formal degree in computer science (or their mathematics equivalent for the more senior participants) and classical music performance as serious avocation. Apart from gender variability, there was no requirement for variation by social class, age or demography. The resulting group of seven participants was composed of two females and five males, 40–80 years old [24]. The relatively small female-to-male ratio reflects the reported small female-to-male ratio of computer-science graduates in the western world, let alone the proportion of working female computer scientists (with over 10 years’ experience) who also seriously study a musical instrument. The interviews were conducted in person and in English, lasting approximately two to a half hours for each participant.

The interview questions covered family and educational background, early music exposure and other interests in the subject’s youth, work experiences, coping with concurrent engagement in the two disciplines, music-making informing thinking in computer-science work and vice versa, career decisions, learning experiences and mentors, and emotional aspects of involvement with the two disciplines. The transcribed interview data was then thematically analyzed within and across participants based on processes described by Glesne [25] and Creswell [26] (i.e. drawing phrases that represent concepts per participant, grouping common concepts across participants into more abstract “meaning units,” and interpreting these “meaning units” and their interrelationships to create themes).

Four primary themes with their associated subthemes have been identified: being in the zone, assuming an engineering/scientific mindset (analytical mind [emergence, expression], spatial/visual [27] abilities), aesthetic thinking and joyous thinking. Although each primary theme is created across at least five participants, it is often demonstrated in this article with fewer representative participants due to space limitations.

**Being in the Zone**

While solving computer-science problems at work or when performing music, study participants reflect on being intensely motivated and focused at their activities, often describing this mental state as “being in the zone.”

When I’m really engrossed in thinking about solving a computer-science problem it’s just the same when I was engrossed in a performance, and you kind of get in the zone. . . . It’s just kind of like you’re hyper-focused. —Megan

When you’re sitting on the stage, all that music is physically flowing through you, the vibrations are moving through you. . . . You are in a sea of people and you are all moving together and you’re responding to each other. . . . It’s a very powerful experience. . . . It’s at the moment . . . it’s almost like an out of body experience. . . . It’s almost like . . . you’re not doing it yourself, you’re looking down on yourself and this stuff is just coming out. —Ethan

These accounts of feeling hyper-focused and in the zone resemble the state of flow described by Csikszentmihalyi [28]. Reaching that mental state of being in the zone provides gratification, empowerment and happiness.

You write . . . 100 lines of code and you run it, and there it is, you see it. . . . There’s this wonderful direct feedback that’s very gratifying . . . very empowering. . . .

You’re playing and ah, you’re experiencing at the moment. . . . The application of producing sound, or whatever you’re producing as an artist, comes back to you instantly. . . . It’s gratifying. . . . You are producing something that for me was very empowering. —Ethan

Csikszentmihalyi demonstrated that flow experienced at work, as well as leisure-induced flow, directly contribute to happiness and work satisfaction.

Evident from the above disclosures is the possibility that the capability of being in the zone originated during the participants’ engagement in music-making and have later transferred to their computer-science engagement. While such a transfer process might occur without the individuals’ awareness [29,30], researchers [31,32] have speculated that such a transfer process might occur without the individuals’ awareness [29,30], researchers [31,32] have speculated that analogical reasoning [33] as well as abstraction resulting from extensive experiences in the source domain [34] play important roles in such transfers.

**Engineering/Scientific Mindset**

Through their reflections on childhood interests, school projects, work assignments and music endeavors, musical computer scientists implied using skills typically associated with an engineering way of thinking, in both music and computer-science activities. These skills include an analytical way of thinking and visual processing of information.

**Analytical Mind**

Analytical skills emerged in these individuals during childhood via their passions for playing and building with construction toys such as Lego blocks.

I always loved building things. . . . I had Legos. . . . I would be playing with them a lot . . . always building things. —Ernie

I spent a lot of time playing, building buildings with Lincoln logs, my father was always doing something fascinating, [like] taking a car apart. . . . All the neighborhood kids . . . would congregate, . . . so we took apart . . . the engine in a VW Bug a bunch of times. —Meg

Ernie’s and Meg’s reflections on their creative tinkering are substantiated by Root-Bernstein and Root-Bernstein [35], who find that playing with classical construction toys helps
kids become designers and inventors through the unlimited opportunities these toys provide for imagination. Indeed, Ernie incorporated a Lego-based, piano-roll scrolling motor in the innovative music-recognition system he developed with his mentor while at the MIT Media Lab.

These analytical skills have been expressed through several thinking modes: pattern-oriented, divide-and-conquer and gestalt. While practicing music of classical and romantic periods, which lends itself to patterns, these individuals would learn to identify patterns.

If you just start playing it initially, you're like: I don't know where this is going, is this atonal or what? But then you look at it more closely and then you realize like . . . it has tonalities, it's just changing it every beat . . . it has this scale, it'll play four notes of a scale in C major, and the next is F sharp major and C major and F sharp major . . . . My personality and the fact that I'm very analytical and the fact that I'm drawn to computer science and building and engineering, definitely . . . has an influence over how I think about music and how I think about practicing.

—ERDIE, on practicing contemporary music

Then it suddenly became necessary to . . . look at music structured, especially piano music, analytically . . . . Piano music really consists of multiple parts very often and recognizing that structure was very important.

—SOL, viewing music analytically while programming his innovative music editor to help composers capture their musical ideas

When the problem does not yield to obvious patterns, these individuals sometimes resort to divide-and-conquer problem-solving.

It seems random, I don't see any patterns . . . there's no particular scale . . . . What do engineers do? They break it down into smaller problems.

—ERDIE, on practicing a complex contemporary musical piece

That's kind of what you do with computer science or when you're doing engineering . . . . You have a big problem . . . . We have to take this huge big elephant problem and turn it into elephant burgers . . . . and that's what really makes it something that you can attack a big problem and be successful.

—MEC, on developing complex genomic systems

Individuals would also think in gestalt mode [36].

I could only go so far with the detail and just had to step back and see how it fits in with the rest . . . . I could stop counting at that point, whereas before that, I was counting like mad to get the exact rhythm . . . . It was quite random, I don't see any patterns . . . there's no possible they were endowed with an innate analytical ability that Gardner [39] terms mathematical-logical intelligence, or that this ability has modularized early on [40].

Spatial/Visual Abilities

In addition to analytical qualities, these musical computer-scientists have been endowed with visual skills.

I was a very good artist, was obsessively interested in maps, and so I would draw maps . . . . not trace them but just sort of draw them freehand . . . . I was the best student at solid geometry . . . . I had very good spatial understanding.

—MEC, on her map drawing, geometry, and directional navigation

I have the part, I just imagine, I look at the tricky parts, and I just plot out which way I should do it . . . . There are typically four physical drums . . . . each drum has a different range, and you have to figure out . . . . if I'm gonna get from these four notes, and I need another note very fast, which one of these am I going to use.

—STAN, simulating his orchestral timpani role at home without the presence of the timpani

I have memorized so many sonatas and concertos that I can dial up something if I'm stuck in the airport.

—ERDIE, using gestalt thinking when managing software development, analogous to orchestrating music

Presence of patterns in musical compositions has been discussed by researchers attempting to relate the disciplines of mathematics and music [37]. Such pattern-recognition activity is perceived as one of the skills used by creative people, as it is essential in discoveries when one perceives new connections between seemingly unrelated things [38]. Given the above individuals’ fascination with structural objects at an early age, and admitting to an analytical predisposition, it is possible they were endowed with an innate analytical ability that Gardner [39] terms mathematical-logical intelligence, or that this ability has modularized early on [40].

Recent studies have shown the importance of visual thinking, in addition to analytical thinking, weakening Arnheim’s [41] claim regarding superiority of analytical ability over visual ability. These studies show that visual ability is trainable [42], is important for certain technical occupations like engineering and understanding chemistry [43], and is the most significant predictor of people’s ability and success in interacting with computers [44]. Moreover, through biographical accounts, R.S. Root-Bernstein [45] shows that visual thinking has been a central thinking tool in the discovery

We rehearse doing the project multiple times, and I call that the dress rehearsal . . . . I'm the type that takes the planning down to, I call it the build level, where everyone knows what they're going to do.

—ERDIE, using gestalt thinking when managing software development, analogous to orchestrating music
and development of technological advances that have had a long-term impact on society. Spatial/visual abilities have been found to be highly correlated with scientific success [46] and contributory to creativity [47]. As music-makers practice these spatial/visual skills simultaneously with aural and kinesthetic skills, it makes musical computer-scientists especially creative [48]. Although several studies, triggered by the controversial Mozart Effect study [49], have reported positive associations between formal music listening and spatial/visual abilities [50], and between music learning and spatial/visual abilities [51–56], the evidence for a causal link is still vague.

Aesthetic Thinking

Aesthetic thinking has been historically practiced and valued more in artistic rather than in scientific accounts [57,58]. However, testimonials by known mathematicians and scientists like mathematician Poincaré [59], mathematician Hadamard [60], astrophysicist Chandrasekhar [61] and biologist/physiologist R.S. Root-Bernstein [62] speak to the appeal of aesthetic themes in their work and identify aesthetics as a motivator for their pursuit of science. R.S. Root-Bernstein [63] also claims that scientific inventions have the potential to evoke aesthetic responses similar to those evoked by the arts.

Participants have expressed various aesthetic qualities through playing music (e.g. emotions, organization) and building computer systems (e.g. design elegance, flexibility, user interface considerations). In addition to expressing pleasure from the effects of these aesthetic qualities, participants have acknowledged their contribution in the practice of these disciplines, thus increasing productivity (e.g. in music: enhancing music memorization, bonding with audience; in computer science: intuitive user interfaces, robust system design).

**Emotionally it’s very satisfying to be playing music. . . . You can really connect with the listeners.**
—Ernie, on the emotional dimension of a musical piece

**I also think of engineering as sort of having a technical thing but then the result can be beautiful too. . . . If you’re programming something, there’s an elegant way to do it.**
—Ernie, believing that software programs can be written to be efficient as well as elegant

**It was so exciting there, because the Media Lab is about computer science and art, or about how society “should” use computers. . . . They think about sorta how technology affects society and people. . . . It’s much more humanistic.**
—Ernie, on the artistic and humanistic aspects of computer science from the user's perspective

The area of software programming has developed its own aesthetics over the past several decades. Knuth [64], a computer scientist and self-taught musician, and Billington [65] have raised aesthetic considerations in the writing of algorithms, programming languages and programs, while MacLenman [66] was equally concerned with design of computer user interfaces. A collection of accounts by computer professionals on the role of aesthetics in computer science [67] bears a resemblance to the role aesthetics plays in artistic domains, and often includes analogies to these domains (e.g. poetry).

Ethan views aesthetics in music through his discovery of a composition’s structural organization, as in Myaskovsky’s cello sonata:

*He has the melody playing along, and underneath it is this inverted sixth, parallel sixths being played, sometimes by the piano, sometimes by the piano and the cello.* —Ethan

Discovery has been explored as theme of aesthetics in both music and mathematics [68,69] and is present in the accounts of scientists and mathematicians (e.g. Gauss’s [1777–1855] flash of lightning when grasping he succeeded to prove a theorem [70]) and musicians (e.g. Hadamard’s [71] assertion of Mozart seeing his symphonies in his mind before putting them down on paper).

Miro and Meg’s sense of aesthetics in computer science is reflected in their concern for both flexible architecture and usability [72].

*They couldn’t expand gracefully, adapt to requirement changes. . . . Look at these big genomics projects, they have tons, dozens of people. . . . If you can’t express what you need, what’s going on, why it’s important, make people care about it. . . . you’re sunk.*
—Meg

*I was very much insisting that, ok, “To be usable it has to have this. . . . a musician is going to demand that.” The result was a program usable by many different kinds of musicians.*
—Miro

One of my executive coaches . . . told me that I always had to be very careful about modulating the information to the audience I was presenting to, and I said, “Well, I know what that is, that’s performing.”
—Meg, on simplifying her computer architecture presentations

*If I’m performing a piece for kids, I do it slightly differently.*
—Meg, accommodating her audience when performing

This theme of simplicity has been considered an important theme of aesthetics [73] (e.g. mathematical proofs that use a minimum of additional assumptions; structural clarity of the classic sonata).

Joyous Thinking

Ethan, Miro, Ernie, Meg and Delia also express their happiness and satisfaction when making music, especially when integrated with parallel work pursuits.

*Music makes me very happy. . . . It’s very important to me in many ways. . . . It helps me pull things from the other side.*
—Ethan

*I kind of need to have music in my life. I need to have computers. . . . I’ve got to have pets. . . . I think I’m happier having all three.*
—Miro

*Overall I think I’m pretty happy. . . . I have these two different experiences that most people don’t have or . . . I think having the two just makes the world much more interesting.*
—Ernie
We went to Hobart and William Smith Colleges... It was to celebrate J.S. Bach's, ah, birthday. ... It was just a really fantastic life experience, where I felt... completely transported. ... I came back to the job, and this was like an exhausting start up job, I mean I worked a billion hours a week, but I came back to the job and I felt more rested, it was as if I'd had a three-week vacation at the beach. — MEG

I feel good when I do this mixture, not only work, work, work.

— DELIA

This aligns with observations made by leisure researchers [74] regarding the possibility of increased happiness and reduced stress, respectively, as a result of engaging in leisure in addition to work.

CONCLUSIONS AND CONTRIBUTIONS

This article describes a rich cognitive toolkit available in the lives of computer scientists with serious music-making avocations. As such, this study can motivate educational institutions to encourage and support individuals with interdisciplinary interests through offering programs designed especially for music and computer-science combinations.

This study also calls for such individuals not to leave behind or minimize their musical interests despite their pragmatic choice of a more stable and financially rewarding computer science vocation but rather combine them in parallel to their practical career.

This study can help educators to better understand learning experiences that make individuals with computer science inclinations happier, challenged, more productive and creative professionals through their practice and performance of music and through combining the two fields in an interdisciplinary fashion.

Finally, this study can help reaffirm (neuro)scientific research on cognitive skills used in the disciplines of music-making and computer science, or provide new directions for such research.

Acknowledgments

I would like to thank Linda Dacey, Diana Dabby and Caroline Heller for help with the design of the overall study.

References and Notes

1 The overall study discusses two additional primary themes: (1) Participation within musical groups; (2) Combining the two disciplines.

The study also discusses secondary themes such as career conflicts and important role of good mentors. The study is described in V. Shaked, “The Meaning of Music-Making for Computer Scientists with a Serious Music-Making Avocation: A Phenomenological Case Study,” doctoral dissertation (Lesley University, Cambridge, MA, 2013).


5 Sociolinguistic analysis, used for analyzing language within its sociocultural context, has supplemented the thematic analysis in the overall study.

6 As recently as 35 years ago, computer science was typically housed within mathematics departments in academia.


9 In a Pythagorean scale, the frequency relationships of all intervals is 3:2 (perfect fifth).

10 12-tone system: a method of musical composition, where all 12 notes of the chromatic scale are given approximately equal importance.

11 Xenakis's stochastic music used probability theory to determine the duration, pitch, timbre and dynamics of the music.


13 Mathematical group (e.g. the set of integers): an algebraic structure consisting of a set of elements and an operation on these elements, such that the application of the operation yields results satisfying some mathematical conditions.

14 Fractals: self-similar patterns, generated by applying an iterative formula to some basic structure, multiple times. Fractals exist in nature, mathematics, music, etc.


21 A two-participant pilot study was performed to confirm the validity of the design of my study.

22 Study Participants*: Ernie (male, clarinetist), Stan (male, timpanist), Delia (female, pianist and clarinetist), Sol (male, pianist; self-learner in music and computer science), Miro (male, pianist), Meg (female, flutist), Ethan (male, oboist and cellist).

Pilot Study Participants*: Dave (male, euphonium/baritone player), Martin (male, pianist).

*All computer scientists; names changed for privacy.

23 Computer scientists work on programming applications, and on the theoretical side of computer systems (e.g. algorithm and data-structure design, systems architecture, computational complexity).
24 Participants were found mostly via word of mouth and the Boston Piano Amateurs Association. The BPAA, founded in 2001, provides performance opportunities, master classes, competitions and workshops for adult amateur pianists.


27 The ability to generate, retain, retrieve and transform spatial/visual images.


33 A theory of analogical thinking in which three constraints of similarity, structure and purpose jointly create coherence in analogical thinking.


35 Root-Bernstein and Root-Bernstein [7].

36 An overall big picture of a situation, where one can see how the smaller details/patterns fall in together.

37 Fauvel, Flood and Wilson [8]; Graves [12]; Rothstein [15]; Chang [18].

38 Root-Bernstein and Root-Bernstein [7].


45 Root-Bernstein and Root-Bernstein [7].

46 Root-Bernstein, Bernstein and Garnier [3].

47 Root-Bernstein and Root-Bernstein [7].

48 Root-Bernstein [4].


The STEAM movement, focused on integrating arts (broadly encompassing visual and performing arts, crafts and design) into science, technology, engineering and mathematics (STEM) education is well underway. We are avid advocates of this movement but worry that integration of arts and sciences into curricula from K–12 through graduate and professional education is not supported by sufficiently rigorous pedagogical studies. If STEAM is to succeed, it must be underpinned by pedagogical principles, methods and materials of high quality and reliability. Toward that end, the Editors of Leonardo have decided to create a STEAM Initiative on Education that will devote a section of the journal to innovative, inspiring and important studies of STEAM pedagogies.

In the spirit of interdisciplinarity, we explicitly welcome diverse methodologies such as mixed methods designs and novel assessment methods designed to meet the special needs of STEAM educators. We particularly welcome studies employing well-designed, randomized classroom controls and utilizing well-validated learning measurement standards, but Leonardo recognizes that one of the challenges of STEAM integration is that it may require new approaches to teaching and learning. We therefore welcome articles that are focused on the development and testing of novel approaches and methods for purveying and evaluating integrated learning.

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