The Hypothesis of Self-Organization for Musical Tuning Systems

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ABSTRACT

Musical tuning systems are found in intriguing diversity in human cultures around the world and over the history of human music-making. Traditional justifications for the adoption of such musical systems consider tuning an algorithmic optimization of consonance. However, it is unclear how this can be implemented in a realistic evolutionary process, with no central entity in charge of optimization. Inspired by the methodology of artificial language evolution, the author proposes that tuning systems can emerge as the result of local musical interactions in a population. His computer simulations show that such interactional mechanisms are capable of generating coherent artificial tunings that resemble natural systems, sometimes with a diversity and complexity unaccounted for by previous theoretical justifications.

INTRODUCTION BY EDUARDO R. MIRANDA

This paper by Jean-Julien Aucouturier won the best paper award of the Workshop on Music and Artificial Life (MusicAL), which took place in Lisbon (Portugal) on 10 September 2007, as part of the European Conference on Artificial Life (ECAL) 2007. Of a total of 26 submissions, only eight were selected for oral presentation at the workshop. Each paper was reviewed by three members of an international program committee composed of 14 scholars. Aucouturier's paper received the highest commendation.

The Artificial Life (A-Life) approach to music is an exciting new development for composers and researchers. For composers, it provides an innovative and natural means for generating musical ideas from a specifiable set of primitive components and processes, reflecting the compositional process of generating a variety of ideas by brainstorming followed by selecting the most promising ones for further iterated refinement. For researchers, A-Life techniques are used to model the cultural transmission and change of a population's body of musical ideas over time. Such models enable the study of the circumstances and mechanisms whereby music systems might originate and evolve in artificially created worlds inhabited by communities of interacting autonomous agents.

Whereas most papers presented at the workshop focused on A-Life systems for composing music, Aucouturier's paper focused on computational modeling of musi-

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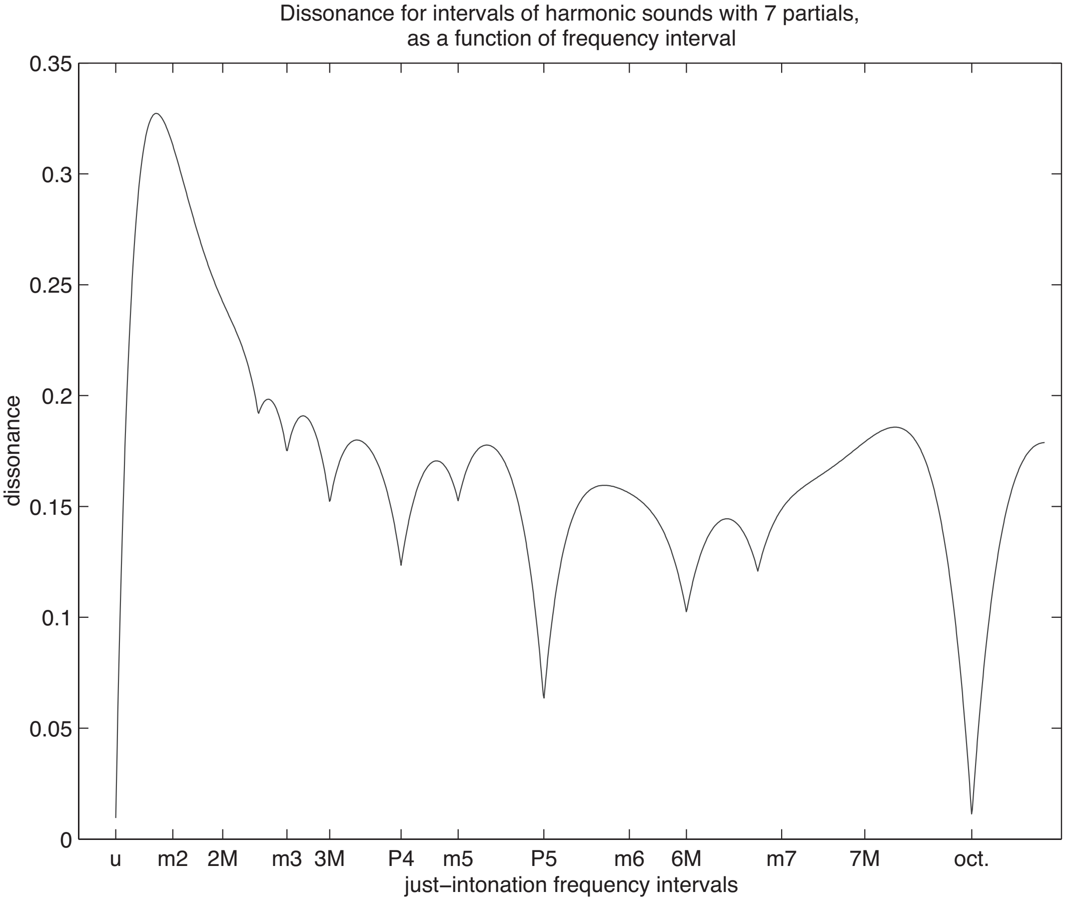

Fig. 1. Dissonance curve for intervals of harmonic tones with seven partials, as a function of frequency interval. The curve is generated using the mathematical parameterization of Sethares [27]. We observe that minima of the dissonance curve correspond to many of the degrees of the "just intonation" tuning system. (Image © Jean-Julien Aucouturier)

cal evolution, more specifically, on modeling the evolution of tuning systems. This is a highly original piece of work, which contributes significantly to the emerging field of evolutionary computer music.

On a superficial level, this paper seems to touch the main theme of this issue of *LMJ* only marginally. I do believe, however, that the possibility of programming machines to evolve their own tuning systems, and indeed music, may have a significant impact on the future of music.

On behalf of the co-organizers of MusicAL, the program committee and all participants, I would like to thank *LMJ* for its unconditional and enthusiastic support of the MusicAL award.

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Considerable attention has been paid to the emergence of linguistic ability in human evolutionary history, with cross-disciplinary efforts over the fields of linguistics, anthropology, neurophysiology or artificial life [1]. However, its musical counterpart has been virtually ignored until recently [2], with awareness emerging only that the cognitive abilities of music-making and listening may be more than secondary outcomes of language capacities and in fact central driving forces in the evolution of the modern human mind [3]. Music-making is a multifaceted behavior, which can be analyzed from a physical point of view (describing the properties of the musical stimuli, e.g. frequency, periodicity, etc.), but also from cognitive (starting from the basic sensations of e.g. pitch, rhythm, etc., evoked by the former) and cultural ones (music is grounded in social interaction, as noted e.g. in [4]). This paper is concerned with only one aspect of the above, namely the question of the evolution of musical tuning systems.

A vast majority of human music [5] is based on discrete sound events in time, or tones, each with a distinct height or pitch. Tone height is a continuous physical parameter (related to the oscillation frequency, in Hertz), but it typically uses only a discrete and finite set of pitch values (e.g. {C, C#, D, D#, . . .} in the Western tradition). The choice of the number and spacing of such frequency values can be defined as a tuning system. Tuning systems are generally periodic, with tone frequencies having a ratio of 2:1 referred to as being of the same pitch class, one octave apart.

Most music in the European/North American world relies on the so-called 12-tone equal-tempered tuning system, a set of 12 pitch values per octave that are equally spaced logarithmically. This is, for instance, the standard system for tuning a piano, where the smallest interval between two keys (e.g. between C and C#) is called a semi-tone (an interval also measured as 100 cents). However, the predominance in our culture of 12-tone equal temperament should not occlude the great variety of other possible tuning systems found in the many examples of indigenous music around the world and over the history of human music-making.

Equal (or "fairly equal") tempered systems using tone numbers other than 12 are found in, for example, central Javanese gamelan *slendro* tuning with five notes to an octave [6] or medieval 19-tone ("one-third-comma meantone") and 31-tone ("one-fourth-comma-meantone") temperaments [7]. Non-equally spaced tuning systems are also common, for example, in the 22-tone Indian musical system, in which the octave is

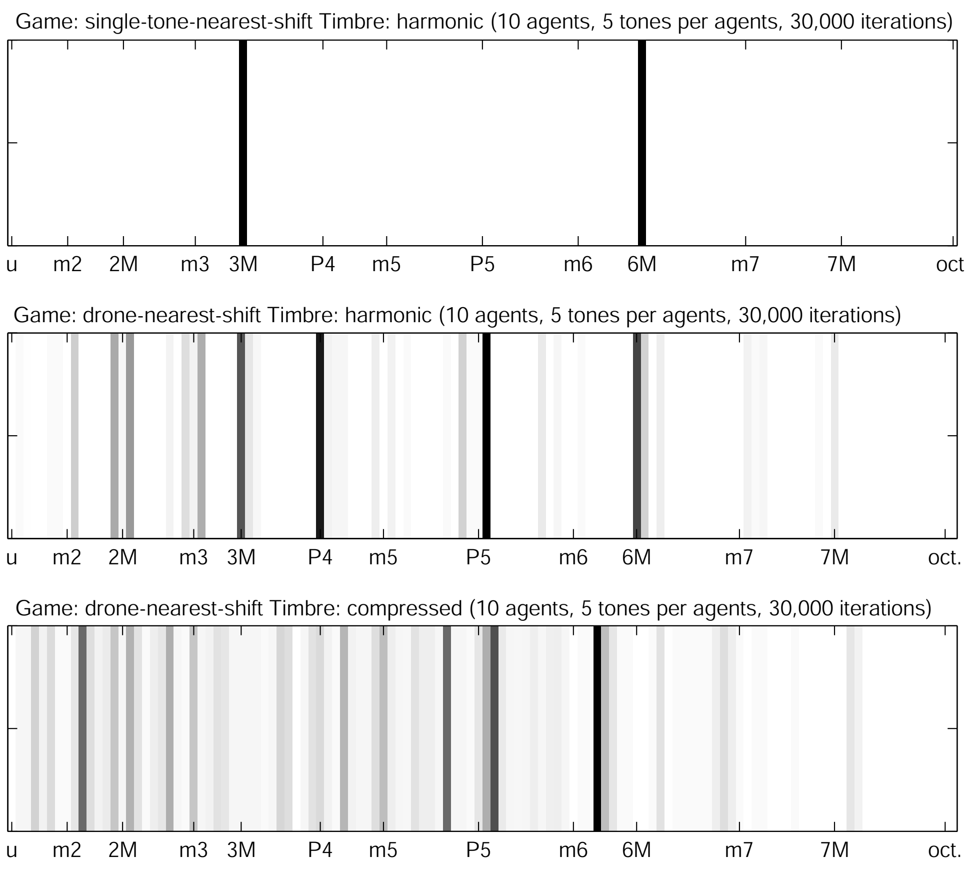

Fig. 2. Interval histograms in tuning systems evolved after 30,000 iterations for different simulation settings. Single-tone-shift games do not reproduce the diversity and complexity of natural systems as well as drone-shift games. (Image © Jean-Julien Aucouturier)

divided into 22 *shrutis,* built with two types of semitones (90 and 114 cents) [8]. In other words, while any tone frequency between 261.626 Hz and 277.183 Hz would only sound to a Western listener as either a high-tuned C or a low C#, other cultures may very well have a word for it and make it a distinct and well-defined pitch class.

The mechanisms by which various human cultures have come to internally decide on conventions to discretize a continuous space such as tone frequency are intriguing and reminiscent of other features of human cultural and cognitive evolution, such as:

- basic color terms (where a space of visual frequencies is divided into classes for "blue," "green," "red," etc. [9])
- vowel sounds in human phonologic systems (from a space of continuous motor commands [10])
- and even the lexicons of human languages (which may be seen as indexing an arguably continuous and infinite symbolic space [11]).

The construction of musical tuning systems is by no means arbitrary and notably obeys strong physiological constraints. Various pitch combinations will sound more or less "natural" (or "pleasant" or "restful") when used in combination, and this sensation of consonance has been found to be quite universal among human cultures, notably due to its maximum manifestation in octave (2:1) and perfect fifth (3:2) intervals [12]. A plausible model of tone consonance was derived by Plomp [13], who found the dissonance of intervals of pure sine waves to be a simple exponentially increasing-then-decreasing function of their frequency ratio.

$$d(f_1, f_2) = \exp^{-a|f_2-f_1|} - \exp^{-b|f_2-f_1|} \quad (1)$$

When considering intervals of complex harmonic sounds made of a series of *n* sinusoidal partials, dissonance can be calculated as the sum of the dissonances of all pairs of partials:

$$d = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} d(f_i, f_2) \quad (2)$$

Figure 1 shows the dissonance curve for intervals of harmonic tones with seven partials (with geometrically decreasing amplitude by factor 0.8) as a function of distance between the tones' fundamental frequencies. It appears that many of the local minima of the curve correspond to pitch classes of the "just intonation" tuning system (a system based on harmonic ratios, which are approximated by the 12-tone equal temperament). Notably, the most consonant intervals are the unison (1:1), then the octave (2:1), then the perfect fifth (3:2), perfect fourth (4:3), etc.

Such physiological evidence provides apparently straightforward explanations of the evolution and creation of tuning systems, which have been viewed notably as

- Solutions of an optimization problem: The degrees of musical scales should correspond to local minima of the dissonance curve [14].
- Outcomes of an algorithmic procedure: Start with a tone, and iteratively add the octave and fifth interval above and below any tone that was previously determined ("Cycle of fifths" construction); start with octave, fifth and fourth, and add the pitch classes corresponding to their three first harmonics [15].

Such explanations indeed promisingly account for many of the properties of actual musical tuning systems. Notably, as dissonance curves depend on instrument timbres (i.e. amplitude and frequency ratio—not necessarily harmonic—of partials), scales are naturally found to adapt to different instruments, thus explaining their cultural diversity. Also, the fact that typical harmonic series cannot be heard easily after the second or third partial can be used to explain the predominance of 7-tone and 9-tone scales in ancient music.

However, it is unclear how such explanations can be implemented in a realistic evolutionary process, where no central entity can be expected to do the optimization. Although recent musical constructions were indeed derived through pure mathematical thinking [16], this seems an implausible process to explain many of the world's indigenous tuning systems, which rather emerged through local interactions in a musically inclined population. I have a guitar and you have one too: Let's just vaguely tune in and play.

In this context, even apparently trivial observations such as the sheer existence of shared pitch categories do require a second look. Under which interactional processes can a population agree on a common set of pitches and not collapse in extreme scenarios where only one pitch is used (the maximally consonant unison interval), or each individual uses its own distinct set? Moreover, there are many properties of human tuning systems that cannot be explained by traditional algorithmic approaches:

- There is great diversity in the number of pitch classes, from the four notes of arguably the world's oldest instrument [17], the 5-tone Javanese slendro, up to the 22-tone Indian system and 25-tone classical Arab tuning. Dissonance curves as shown in Fig. 1 account for only a limited number of degrees, mainly a function of the number of partials (which does not extend to 20 or more).
- Even within the Western 12-tone system, many intervals such as minor second (C–C#) or augmented fifth/minor sixth (C–G#) are not easily explained by dissonance-based algorithms.
- Tones forming very dissonant intervals (sometimes less than a semi-tone) are often found to co-exist in a given tuning system (and do not fuse into one another), etc.

I examine a few of these aspects with the help of computer simulations in which tuning systems evolve through exclusively local interactions in a population of adaptive agents. Inspired by the ideas of artificial language evolution [18], I try to evolve artificial tuning systems with properties similar to the natural ones, through musical equivalents of language games.

METHODS

Let us simulate the evolution of artificial tuning systems using the methodology of language evolution research along the lines of Steels [19]: A population of agents, each equipped with a simple cognitive architecture (in this case a model of tone consonance perception and a tuning system, i.e. a set of tones), engage in one-to-one musical games (i.e. "trying to play music together"). Game by game, the agents adapt their internal tuning system to increase the success of further games. Let us study how shared tone categories can emerge among the total population and how their properties depend on the distributed activities of the agents. This mechanism, when successful, strongly opposes the previous algorithmic justifications for the emergence of human musical tuning systems: In my framework, there is no central agency that controls how agents are supposed to act.

Agent Architecture

The agents A_i are equipped with simple cognitive structures, each of which is inaccessible to other agents:

- A tuning system $ts_i = \{t_i^1, \ldots, t_i^{N_i}\}$, that is, a set of N_i tones. Tones are described by a fundamental frequency $f(t_i^k)$, and a timbre $T(t_i^k)$, which is given as part of the agents' environment (see the section Environment below). The fundamental frequencies of each agent's tones are initialized at random. In all the experiments reported here, all agents have tuning systems of the same size, i.e. $N_i = N \forall i$
- A tuning procedure, that is, the ability to change the fundamental frequency of part or all of the tones in ts_i
- A restricted model of human hearing simulating the perception of tonal consonance. The model uses the mathematical parameterization of the experimental Plomp-Levelt curves [20] given in Sethares [21]: It computes a value of dissonance $d(t_1, t_2) = d(f(t_1), T(t_1); f(t_2), T(t_2))$ for two tones t_1 and t_2 given by their fundamental frequencies $f(t_1)$, $f(t_2)$ and their timbres $T(t_1)$, $T(t_2)$.

Agents are able to produce sounds for interaction with other agents simply by playing a tone or a series of tones from their internal tuning system. In the current experiment, the agents are only capable of monophony, that is, tones are only played one at a time.

Interaction Protocol

In the experiments reported here, let us investigage two different musical games. Both games, which can be regarded as imitation games as in De Boer [22], are designed to allow the agents to align their internal tuning systems with that of other agents, in a way that enables realistic musical interaction. At each new game (or iteration), two agents, a *player P* and a *tuner T,* are drawn at random from the population. Their interaction depends on the type of game.

Game 1: Single Tone Shift.

This game corresponds to the very simple musical situation where two agents play a single tone at unison, and one of them (the tuner) tries to adapt its tone to generate a consonant interval with the other agent's. The player P and the tuner T draw one single tone at random from their internal tuning systems: $t_P \in ts_P$ and $t_T \in ts_T$. The tuner agent T shifts the fundamental frequency of its tone t_T so as to minimize dissonance with t_P, i.e.

1. finds the frequency value f^* corresponding to the nearest dissonance minimum around $f(t_T)$, i.e.

$$f^* = \arg\min_{f_m} |f_m - f(t_T)|; f_m \in \mathcal{M} \quad (3)$$

   where $\mathcal{M}$ is the set of all frequencies f corresponding to local minima of $d(f, T(t_T); f(t_P), T(t_P))$.
2. deletes t_T from tuning system ts_T
3. inserts new tone t_T^* in ts_T having $f(t_T^*) = f^*$ and $T(t_T^*) = T(t_T)$.

Game 2: Drone Shift.

In this game, a single note is continuously sounded by agent T, in harmony with all the tones in agent P's tuning system. Such accompaniment is called a drone note, and is systematic in many forms of traditional music—often parts of musical instruments are designed to produce such drone notes without requiring the attention of the player, for example, sympathetic strings in Indian sitar or drone pipes in Irish *Uilleann* pipes [23]. More precisely, the tuner T draws one single tone $t_T \in ts_T$ at random from its internal tuning systems. The player P plays all the tones in its tuning system. Agent T shifts the fundamental frequency of its tone t_T so as to minimize the sum of the dissonance with all tones in ts_P, that is,

1. finds the frequency value f^* corresponding to the nearest dissonance minimum around $f(t_T)$, i.e.

$$f^* = \arg\min_{f_m} |f_m - f(t_T)|; f_m \in \mathcal{M} \quad (4)$$

where $\mathcal{M}$ is the set of all frequencies f corresponding to local minima of

$$\sum_{t_i \in ts_P} d(f, \mathcal{T}(t_T); f(t_i), \mathcal{T}(t_i))$$

2. deletes t_T from tuning system ts_T
3. and inserts new tone t_T^* in ts_T having $f(t_T^*) = f^*$ and $T(t_T^*) = T(t_T)$.

Environment

The environmental constraints imposed on the agents mainly concern how tones are implemented. Here, we define a tone t as a series of N_t sinusoidal oscillators, or partials, each with a frequency in Hz and an amplitude, i.e. $t = \{f_i, a_i\}_{i=1:N_t}$. The frequency of a tone's first partial is referred to as its fundamental frequency $f(t) = f_1$. The parameters of a tone's partials for $i \geq 2$ are determined by its timbre $T(t)$, which can be understood as representing a given musical instrument. In this work, we consider two alternative timbres.

Timbre 1: Harmonic Timbre.

This is the timbre of an ideal harmonic sound body (i.e. a string), where the partial's frequencies are integer multiples of the fundamental frequency, with a geometrically decreasing amplitude:

$$f_i = i f_1 \quad (5)$$

$$a_i = \alpha^i a_1 \quad (6)$$

$$(7)$$

where $\alpha = 0.8$ and $a_1 = 1$.

Timbre 2: Compressed Timbre.

This is an inharmonic timbre with partial frequencies not integer multiples on a fundamental, but rather more narrowly spaced according to a geometrical law (we take here the formulation of Sethares [24]. Such timbres are typical of certain bells, such as the 2,500-year-old Chinese *zheng* bells [25].

$$f_i = A^{\log_2(i)} f_1 \quad (8)$$

$$a_i = \alpha^i a_1 \quad (9)$$

$$(10)$$

where $A = 1.90$, $\alpha = 0.8$ and $a_1 = 1$.

All tones are generated using N_t = seven partials. Fundamental frequencies f_i for all agents are constrained to be in the range of 262–523 Hz, corresponding to the octave between C4 and C5 in the 12-tone equal temperament system (this includes the notorious diapason $A4 = 440$ Hz), both at initialization and during updates in musical games. All frequencies are quantized to the nearest 10 *cents* (i.e. a tenth of a semi-tone), which corresponds to the frequency resolution achieved by professional piano tuners.

Measures

In the experiments reported here, I mainly focus on two properties of the evolved artificial tuning systems:

- Number of distinct tones: This measures the number of

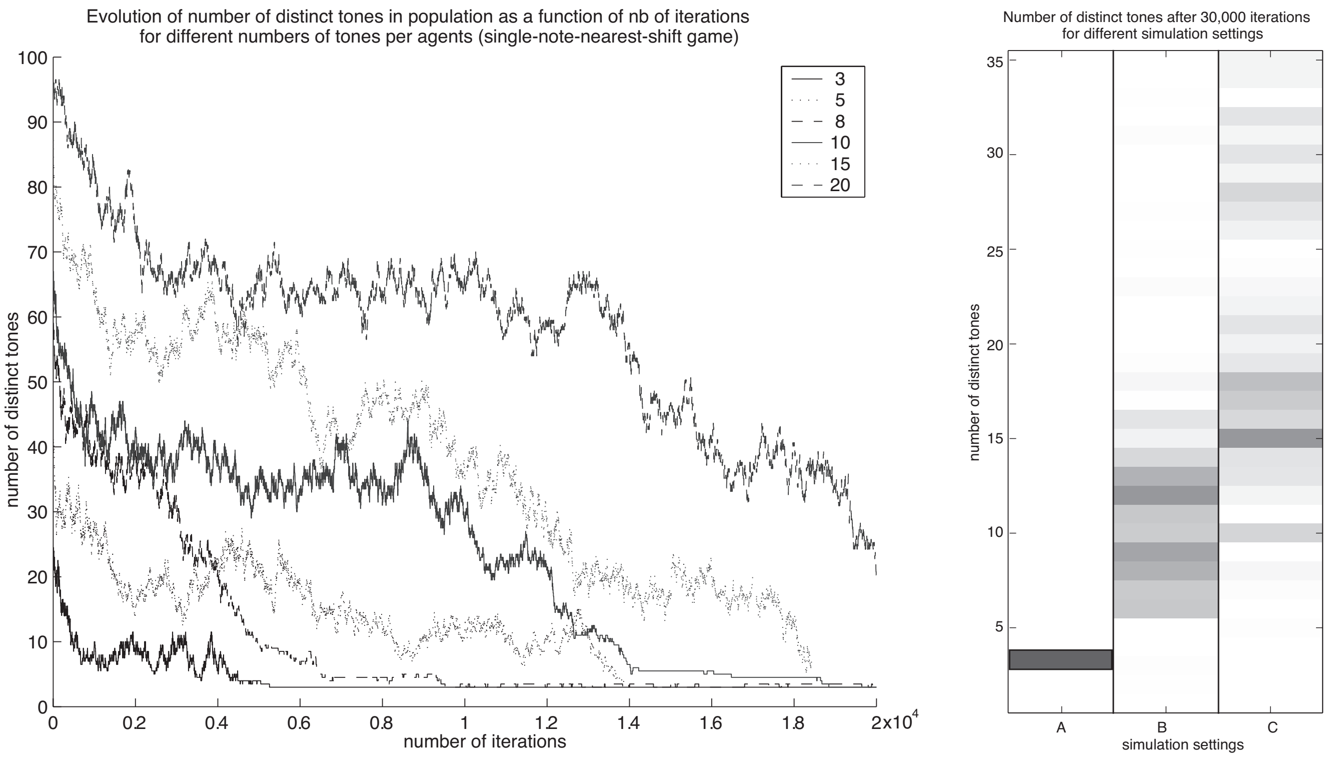

Fig. 3. Left: Convergence profile (in number of distinct tones against number of iterations) for single-tone-shift game and varying number of tones per agents $N \in \{3, 5, 8, 10, 15, 20\}$. All settings converge to (the same) three tones, with speed correlated to N. Results averaged over 10 runs. Right: Comparison of the histograms of number of distinct tones after 30,000 iterations for different simulation settings. A: single-tone-shift game, 10 tones per agents, 10 agents, harmonic timbre. B: drone-shift game, 10 tones per agents, 10 agents, harmonic timbre. C: drone-shift game, 10 tones per agents, 10 agents, compressed timbre. Results averaged over 50 runs. (Image © Jean-Julien Aucouturier)

distinct fundamental frequencies found in the total population at a given iteration *n*. Upon (random) initialization, the number can be as high as $\sum_{i=1}^{N_a} N_i$ where N_a is the size of the population and N_i the size of the tuning system of agent A_i. Low counts of distinct tones after *n* iterations, if observed, show that a limited, shared set of tones has been evolved through local interactions; actual numbers can be compared to natural tuning systems.

- Distribution of intervals: This measures the histogram of the intervals in the tuning systems of each agent in a population, at a given iteration *n*. Intervals in an agent's tuning system *ts* are measured as differences of fundamental frequency of each tone to the lowest tone is *ts*. A 5-tone tuning system $\{t_1, \ldots, t_5\}$ (ordered by increasing fundamental frequency $f(t_i)$) yields four intervals $\delta_i = f(t_{i+1}) - f(t_1) \forall i \in [1, 4]$. The global histogram shows the proportion of such intervals over the whole population. Upon initialization, the interval histogram over the whole population shows a random distribution. Peaky and sparse histograms, if observed after n iterations, show that tuning systems of individual agents have evolved to share the same structure.

Results

The Conditions for Self-Organization Are Non-Trivial

Simulations involving simple games don't converge to anything resembling natural tuning systems. Figure 2 compares the histograms of tone intervals in the global population of agents for different simulation settings after 30,000 iterations, averaged over 50 runs. We observe that interactions based on the single-tone-shift game systematically produce unrealistically simple tuning systems with three tones. The tones are separated by a major third (3M) and a perfect fourth (P4), that is, they span a major sixth interval (6M). This forms a minimalistic-yet-usable musical system, but doesn't reproduce the diversity and complexity of natural systems. Moreover, the convergence under such an interaction protocol seems to be independent of the number *N* of initial tones in each individual agent. Figure 3 (left image) shows the convergence profile (in number of distinct tones against number of iterations) for $N \in \{3, 5, 8, 10, 15, 20\}$. All settings (averaged over 10 runs) converge to the same set of three tones, at a speed correlated with *N*.

Specific Musical Constraints Are Needed

Other more complex musical situations, as implemented with, for example, the drone-shift game, do favor the emergence of more realistic tuning systems, notably:

- Emergence of shared pitch class in a given population, but not the same ones for different runs
- Increased diversity of system size: Figure 3 (right image) shows that, at constant simulation settings, tone numbers form a bell-like distribution with notable variance
- Realistic sizes: between five and 15 tones for harmonic timbres (Fig. 3 [right image, B]), which is in accordance with many natural systems found the world over
- Interval complexity: Emerging systems include strong components at very consonant intervals (P5, P4, 3M, 6M), in accordance with algorithmic constructions based on the Plomp-Levelt consonance curves. However, typical systems also incorporate more dissonant intervals found in 12-tone equal temperament, but not well explained by previous hypotheses, notably minor second (m2) and major seventh

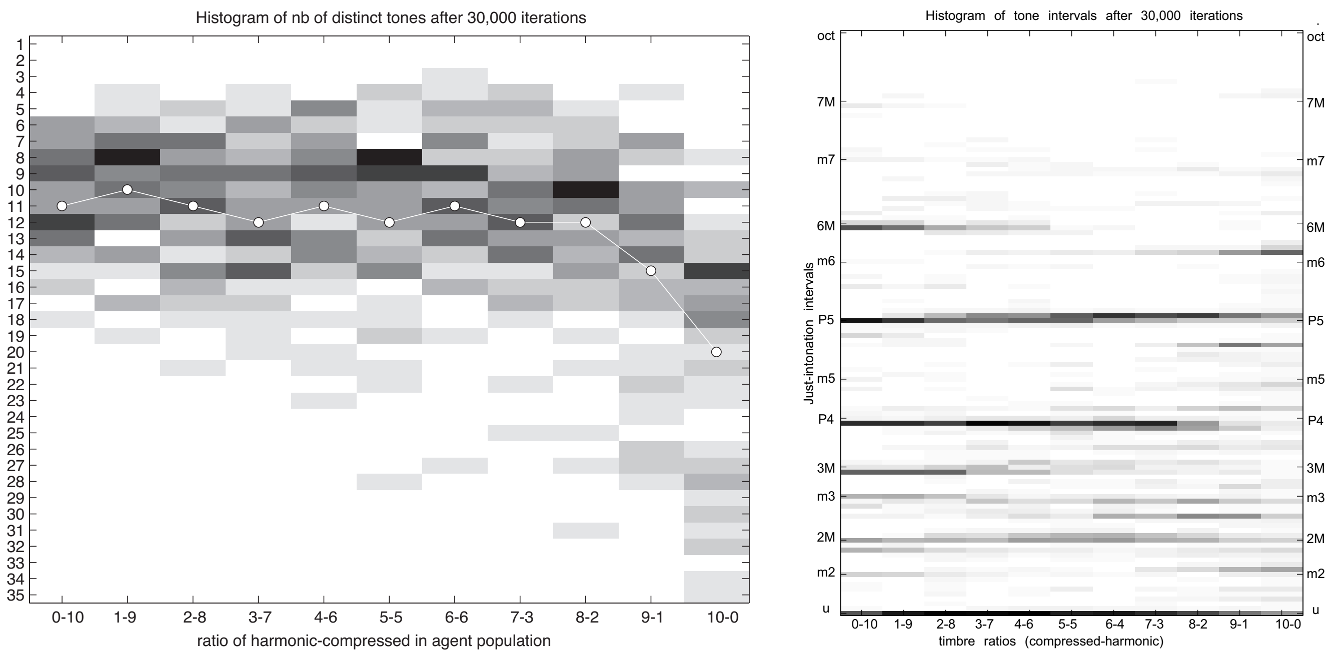

Fig. 4. Left: Histogram of number of distinct tones in tuning systems evolved after 30,000 iterations with heterogeneous populations of agents of varying timbre ratios (far left: purely harmonic, far right: purely compressed). White circles identify distribution means. (Settings: population of 10, 10 tones per agents, drone-shift games, results averaged over 50 runs.) Right: Interval histograms of tuning systems evolved after 30,000 iterations with heterogeneous populations of agents of varying timbre ratios, same settings. (Image © Jean-Julien Aucouturier)

(7M). Moreover, the observed interval distributions also suggest the possibility of emergence of rare non-harmonic intervals, such as low minor thirds (m3) and in between P5 and m6.

On the whole, these observations suggest that certain properties of musical activities, such as the primitive harmonic accompaniment translated with one-to-many drone tuning, are needed to explain the emergence of natural tuning systems.

Instruments Are a Clear Evolutionary Factor

It also appears (in accordance with Sethares's work [26]) that the choice of a given timbre (or instrument) influences the emergence of certain intervals as well as the size of tuning systems. Figure 3 (right image, b and c) shows that, all other conditions held equal, compressed timbres encourage the emergence of tuning systems with more distinct tones than harmonic timbres and also generate greater size diversity over several runs. The structure of systems evolved with compressed timbre is also quite different from the harmonic ones (Fig. 2): strong perfect fifth (P5), no major third (3M) nor perfect fourth (P4) and clear non-harmonic intervals (between m5 and P5, m6 and 6M, m2 and 2M).

Population Heterogeneity Is Another Factor for Diversity

Finally, it appears that environmental factors leading to heterogeneity in the population of agents favor the emergence of even more complexity in tuning systems. We investigate populations of agents made of two groups of varying relative sizes, each with a different timbre (harmonic or compressed). We find that intermediate settings between harmonic-only and compressed-only generate hybrid, interpolated properties in the evolved tuning systems, notably:

- Hybrid number of distinct tones: Figure 4 (left) shows the histograms of number of distinct tones for different timbre ratios, after 30,000 drone-shift iterations, averaged over 50 runs: ratios intermediate between 0–10 (harmonic only) and 10–0 (compressed only) generate intermediate numbers of tones (notably at high ratios), as well as intermediate variance values.
- Hybrid intervals: Figure 4 (right image) shows the histogram of intervals in the tuning systems converged with different timbre ratios after 30,000 iterations, averaged over 50 runs. It appears that timbre hybridization generates systems with mixtures of harmonic and inharmonic intervals:
  - inharmonic intervals (characteristics of compressed timbres) such as high-tuned m6, high P4, high m2 and low P5 appear as early as (4–6), (5–5), (7–3) and (8–2) respectively
  - harmonic intervals such as m2, 6M, 3M and P4 disappear when ratios increase over (2-8), (4–6), (5–5) and (8–2) respectively.

Furthermore, at intermediate ratios, hybridization also favors the emergence of alien intervals that belong neither to the purely harmonic nor to compressed systems and stably co-exist with neighboring intervals, for example, high-tuned 2M from (2–8) to (8–2), and high-tuned 3M from (2–8) to (6–4).

Conclusion

The results of these simulations show that coherent musical tuning systems can emerge as the results of local musical interactions between the members of a population. The artificial systems that emerge show properties similar to the ones found in natural tuning systems, such as number of distinct tones and intervallic structure. Moreover, such self-organizing systems are evolved with a diversity and complexity that is not easily explained by previous theoretical justifications based on algorithmic procedures. For instance, under certain conditions, systems are found that include 20 tones or more, with inharmonic ratios that are alien to the consonance profiles of the timbres used in the population. This is in remarkable accordance with the structure of much-debated tunings such as the ancient Indian 22 *shrutis* system. On the whole, this makes self-organization a promising hypothesis for explaining some of the properties of natural tuning systems.

However, my simulations also show that the implementation of such mechanisms into a realistic interactional framework requires non-trivial environmental and cultural constraints. Simple musical games, in which tones are adapted on a one-to-one basis, are insufficient to generate tuning systems with diversity and complexity resembling that of real-world systems. Advanced musical concepts, such as harmony (e.g. with drone tones), and non-homogeneity in the population (e.g. making music with different types of instruments simultaneously), seem to be necessary ingredients. This suggests directions for future research, for example, incorporating more advanced musical concepts such as melodic interestingness (optimally consonant phrases are boring), or the need for key modulation (which is one of the reasons for preferring the imperfect equal-temperament over just-intonation systems).

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26. Sethares [14].

27. Sethares [14].

Jean-Julien Aucouturier was born in France. He is an electronic engineer trained at Ecole Supérieure d'Electricité, Rennes, France (2001), and holds a M.Sc. in Music and Audio Processing from King's College, University of London, U.K. (2001). From October 2001 to April 2006, he was an Assistant Researcher with SONY Computer Science Laboratory, Paris, France, after which he received a Ph.D. degree in Artificial Intelligence from the University Paris VI, France (2006). In May 2006, he was an invited Research Fellow at the AHRB Research Centre for Cross-Cultural Music and Dance Performance, School of Oriental and African Studies, University of London, U.K. Since November 2006, he has been a Post-Doctoral Research Fellow at the Japanese Society for the Promotion of Science, in Takashi Ikegami's Laboratory, University of Tokyo, Japan.

CALL FOR PAPERS

Nanotechnology, Nanoscale Science and Art

Leonardo Special Section

Guest Editors: Tom Rockwell and Tami I. Spector

Over the last decade, "nano" has become *the* buzzword signifying everything from imagined atomic-scale robotic utopias to small electronics. For scientists the shift toward nano has also become ubiquitous; what used to be referred to as "molecular" has been reframed as "nano," 27 journals devoted to nanotech/nanoscience are now published, and the National Science Foundation and other granting agencies have devoted a significant amount of funding toward nanotech/nanoscience. Among engineers, scientists and science-studies scholars, discussions of the potential of nanotech/nanoscience abound, including conferences that debate the pros and cons of a nano-hegemony and attempt to debunk some of the hype. Artists, however, have only begun to explore this emergent scientific field, leaving it wide open for creative interpretation. With this special section of *Leonardo* we hope to ignite artists' interest in the exploration of nanotech/nanoscience and encourage scientists, scholars and educators to contemplate the implications of an art-nanotech/nanoscience connection.

Leonardo, in collaboration with the Exploratorium under the auspices of the Nanotech Informal Science Education Network, will publish a series of special sections periodically over the next 5 years exploring the intersections of nanotech/nanoscience and art. We are especially seeking submissions of artworks (visual, performance, sound, etc.) with artists' statements explaining the relationship of the work to nanotech/nanoscience; essays from scientists, engineers and scholars exploring the connection between nanotech/nanoscience and art; and essays and visuals aiming at nanotech/nanoscience education that uses the arts as a pedagogical tool.

Articles published to date as part of this special project include:

Tami I. Spector, "Introduction: Nanotechnology, Nanoscale Science and Art," *Leonardo* **41**, No. 4.

Filipe Rocha da Silva, "Nanoscale and Painting," *Leonardo* **41**, No. 4.

Boo Chapple with William Wong, "Can You Hear the Femur Play? Bone Audio Speakers at the Nanoscale," *Leonardo* **41**, No. 4.

Jane Bearinger, "Chaos Control on the Nanoscale," *Leonardo* **41**, No. 4.

Interested artists and authors are invited to send proposals, queries and/or manuscripts to the Leonardo editorial office: Leonardo, 211 Sutter St., Ste. 501, San Francisco, CA 94108, U.S.A. E-mail: <isast@leonardo.info>. Editorial Guidelines for Authors can be found at <www.leonardo.info>.

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