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Symphony of Eigenvalues:
A Prototype for Sonification in System Dynamics

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Abstract

Sonification is the use of nonspeech audio to convey information and can enhance the ability of system dynamics in the analysis of relationships between structure and behavior. Today's desktop computing power allows users of software such as MAX and MSP to create a variety of sounds whose parameters are determined by the mappings of imported data. The prototype discussed used pitch, timbre and amplitude to describe the values and first and second order differences, respectively, of the state variables. A two-parameter model of Hares and Lynx demonstrated the sonic effects, while another two-parameter model of Alcohol and Cells featured the addition of sonified eigenvalues, illustrating the combined fields' potential to provide an early warning detection to changes in feedback loop dominance. The prototype's ability to express 10 parameters of interest with just 4 sounds should appeal to the fields of business, education and the arts.

Keywords: sonification, auditory display, system dynamics, learning environment, educational psychology, human-computer interface, simulation, eigenvalue analysis.

Introduction

We are living in what is commonly called the Age of Information and are challenged to manage the ever-increasing flow of information as computing power continues to increase. While more information is readily accessible, we are not necessarily selecting, filtering, processing and recalling information any better. At the same time, technology offers tools to aid in understanding our world of increasing complexity, tools such as system dynamics and sonification, "the use of nonspeech audio to convey information" (Kramer *et al*. 1997: 1). This paper focuses on how sonification can enhance models in system dynamics to better understand relationships between structure and behavior in complex environments.

Technology offers synergistic benefits to the learner by using a combination of senses to optimize information processing and demonstrate the many underemphasized links between categories of study**.** Specifically, we champion the link between sonification and system dynamics as a superior method for demonstrating the insight that eigenvalue research provides to complexity. The prototype model is also discussed to illustrate some of the many ways and potential benefits of combining audition with system dynamics in studying complex dynamic systems.

Overview

Inasmuch as this research lies at the intersection of several disciplines–music, system dynamics, perceptual psychology and learning theory–it is likely that some experts in one of these areas may not be well acquainted with concepts in another. We therefore provide an overview, concentrated in the fields of music and perception, since both fields affect the cognitive effect of sonification on the listener. There is, in addition, a Gestalt quality to music that makes the overall sound more meaningful than the sum of the parts. Concepts of music and perception, along with styles of learning, must be carefully considered in building a methodology for sonification, despite the fact that the complex tones featured in the discussed prototype may not be considered by most to be "music."

Tones

Tones are produced by our auditory response systems from sound waves. While the physiologic and neurologic aspects of audition and the perception of tones are complex and not fully understood, let us conceptualize a tone as created by a vibrating string that creates differences in sound pressure traveling in sinusoidal waves. We can identify for each tone a fundamental frequency measured in cycles per second, or Hertz (Hz). In addition, when a musical tone is played, it often has harmonics: sound waves at higher frequencies that are integer multiples of the fundamental frequency. Harmonics add to a tone's complexity and brightness; in fact, the fundamental does not even have to be present in the tone (Cook 1999).

Most tones have the properties of pitch, loudness and timbre, which are physically correlated with–though not identical to–frequency, amplitude and harmonics, respectively. Duration, another property of tones, is often described in terms of the attack, steady state, and decay of a sound wave (Dodge 1997). Each of these segments influences our perception of the tone, as do other aspects of tone sequences such as melody and rhythm. Tonal properties are perceptually interdependent. A melody, for example, can lose its coherence if the pitches change drastically from one note to the next.

Pairs of tones whose fundamental frequencies are at a ratio of 2:1 are called octaves. Musical sets of pitches defined within an octave are known as scales. Scales are logarithmic and are built on perception. In addition, the tonal center's harmonics, which have frequencies that are multiple integers of the tonal center's fundamental frequency, have pitches that seem particularly consonant with the tonal center. Although our musical backgrounds have likely made us particularly familiar with the sounds of triads, the relationships in vibrational frequency between triadic tones may also be a reason for their pleasing quality. Krumhansl (1979), in experiments with musically-trained listeners, found the tones of a major triad chord were judged more similar to one another than other tones played in a pre-defined scale.

Our sensitivity to pitch is another reason why it is a critical issue in sonification. For those with unimpaired hearing through early adulthood, auditory sensitivity ranges from approximately 20 to 20,000 Hz, or about 10 octaves, and is most acute at around 1000 Hz (Buser 1992). We are capable of discriminating between two tones having a difference of only 0.5 to 2.0 Hz at low and middle frequencies. This ability, combined with the ability to discern very subtle differences in intensity, creates a great number of perceivable combinations, although we are still bound to Miller's 7 ± 2 short-term memory rule, i.e., that we are only able to identify five to nine sounds that vary along only one attribute (Handel 1989).

Loudness

Our perception of loudness correlates with the amplitude of the sound wave. The amplitudes of the harmonics are usually smaller than that of the fundamental, but the variation in the relationships of harmonic amplitudes for a given tone largely affect the quality of the sound. (See *Timbre*.) In accordance with our perception of the extreme range in intensity of audible sounds, logarithms are used to express intensity of two tones with sound pressures P1 and P2 in decibels (dB) (Handel 1989):

decibels = 20(log P1 – log P2)

By convention, 0 dB describes the threshold of audibility; a quiet conversation or soft music is 60 dB and the threshold for *feeling* sounds is 120 dB. However, sounds with a frequency outside the range of 1,000 to 6,000 Hz are perceived as quieter than sounds of equal intensity within this range. Also, our perception of increases in loudness does not match increases in sound pressure (in decibels). For example, two identically sounding instruments sound only 1.6 times louder than one (Handel 1989).

Timbre

The quality or color or “timbre” of a sound is a result of the combined harmonics and the perception of how they vary over time, and is the main parameter used to differentiate between different musical instruments. Some pairings of two different instruments are perceived as being less similar in timbre than other pairs, although such perceptions are affected by interactions and environmental conditions. Melara and Marks (1990) found recognition and classification of pitch and timbre to be correlated, demonstrating that one’s timbral perception of an instrument may be different at different pitches.

Rhythm

Rhythm illustrates a Gestalt aspect of music; i.e., our perception of individual rhythmic elements is largely dependent on expectation, and thus can only be studied in the context of the whole. With rhythm, we tend to group elements into twos, threes or fours using a variety of variables, and our perceptual grouping is highly sensitive to small changes. Handel explains that “in order for individual elements to emerge as rhythmical accents, the onset-to-onset tone interval must be within certain bounds; beyond about 1.5 seconds, two elements lose a sense of coherence and appear unrelated” (1989: 389).

Perception

Perception affects what we hear in a variety of ways and is therefore of paramount importance to building a methodology in sonification. To understand the importance of pitch perception, consider the familiar Doppler effect, a perceptual phenomenon of hearing the pitch of a train engine or race car drop as the vehicle speeds by. Further, Chowning (1999) refers to the difficulty in identifying the voice of a singer without the inclusion of periodic and random variation in pitch, and Buser (1992) describes the *mel*, a unit of pitch level at a specified amplitude, in explaining that perceived pitch above 1000 Hz rises less than linearly with frequency.

Additional perceptual phenomena arise when we combine tones of different frequencies. “Beats” occur when we hear two continuous tones at separate pitches slowly merge in pitch. These beats, caused by constructive interference between the sound waves, slowly disappear as the frequencies converge.[i] Even if we listen to the sounds by separate left and right channels through headphones, so that the two tones are not interfering with each other, our auditory system *creates* the interference, known as “binaural beats” (Dobrian 1998: 45). A visual parallel is the perception of a car’s wheels momentarily seeming to spin backwards when the vehicle accelerates through a particular speed. A more problematic perceptual phenomenon is masking–the perceived dominance of a tone at a lower frequency over a tone at a similar but higher frequency–which can be particularly problematic in three-dimensional auditory displays (Gilkey 1995).

One’s musical knowledge is another key component to understanding perception because it affects our expectation of what we might hear next. Piro (1993) found that musical background has an effect on the asymmetric bias for how sounds are perceived. Knowledge particularly affects rhythmic perception, despite our acuity for distinguishing between periodic and aperiodic events (Kramer *et al*. 1997). When we do not know what to listen for, our ability to discriminate patterns among similar tones is limited to Miller’s 7 ± 2 rule. However, since tonal and rhythmic patterns are perceived holistically, training may develop the listener’s ability to focus on certain critical elements of the pattern while hearing the rest of the sounds as a chunked group. Espinoza-Varas and Watson (1989) suggest the process of gaining fluency of a foreign language as an illustration of how we link our perception of hearing to cognitive strategy, and of how hearing is therefore largely a matter not of the ear but of the brain.

Other perceptual phenomena in music that should be considered in building a methodology for sonification include audio electronics and the listening environment. The marriage of electronics, digital technology and music has spawned many new sonic possibilities, but always with audibly perceptible limitations from error and distortion, particularly in the recreation of recorded sound. Of particular importance is the Nyquist frequency, a limit equal to half the sampling rate (44,100 Hz for CDs). The sampling rate is the amount of instant values of the sound pressure curve sampled per second. The Nyquist theorem states that the computer can only accurately represent frequencies up to half the sampling rate. Higher frequencies will be folded back and perceived as lower frequencies. To avoid this misperception, a low pass filter is applied prior to the analog-to-digital converter to eliminate frequencies above the Nyquist rate (Dobrian 1998).

A key environmental issue concerns the change in perception for reflected sounds arriving at different times. Termed the Haas effect (Handel 1989), our perception will cause us to hear a single sound if a similar one is reflected off a barrier and arrives within about 30 milliseconds of the direct sound. Our perception is also susceptible to visual suggestion. Rasch (1979), for example, determined that we perceive musical performers as playing “together” (as one) if their tones are not more than 50 milliseconds apart. This paradox highlights the influence that context puts on our perception.

Learning Styles

A looming question concerning the use of an uncommon learning tool such as sonification is whether some learners will benefit more than others, and if so, who and why? Does sonification as a tool for studying complex systems offer greater benefits to musicians than non-musicians? That sonification should offer benefits to the visually impaired may seem obvious, yet the full reasons may not. Walker and Lane (2001) have found differences between sighted and visually impaired listeners in the general population as to how sounds are used to represent data. Furthermore, it is predicted that among the visually unimpaired, the distribution of benefits that sonification provides to a learning environment will fall into clusters. Musical experience or proficiency may explain such clusters, since musically proficient people may be more adept at quickly interpreting information conveyed through sound.

Yet another variable might be found in preferred methods of learning. Gardner's (1983) theory of multiple intelligences has sparked interest in redefining mental achievement and in more closely examining sensory modes for receiving information. Certain modes or combination of modes may particularly suit some learners. Learning styles[ii] show preferences in receiving information and are commonly divided into at least three categories: auditory, visual, and tactile-kinesthetic. People who prefer an auditory learning style may particularly benefit from sonification.

Eigenvalue Analysis

Having addressed a number of concepts relevant to building a methodology for sonification, we now turn to concepts in system dynamics that aid in understanding complexity. Recent research involving the use of eigenvalues offers new opportunities to more thoroughly analyze and understand complex systems. Eigenvalues are typically introduced in linear algebra as scalars (commonly referred to as λ) that, for an n-by-n matrix A and a vector v, satisfy the equation $Av = \lambda v$. In two- or three-dimensional contexts, we can think of A as lengthening, shortening or reversing v, depending on whether λ is positive and greater than one, positive but less than one, or negative, respectively (Anton 1984).

Readers not familiar or not comfortable with the mathematics of eigenvalues may choose to think of them as mathematical correlates to pleasing, simplistic frequencies heard when plucking instrument strings or hitting solid objects. There is often a certain naturalness to an instrument, or to a system. A non-auditory manifestation can be found in discovering that a solid, untapered column supporting the weight of a ceiling is not as strong as a column tapered at the points ¼ and ¾of its height. Such nodes were discovered through eigenvalue analysis. In fact, the principle of system nodes or natural frequencies can be extended outside the auditory domain to such fields as bridge construction and oil exploration. Consequently, these fields have benefited from eigenvalue analysis (Carter 2000).

The present project utilizes research that builds on the theory of eigenvalues to show the causal link between a simulation model's structure and its behavior (Saleh & Davidsen 2000). Myrtveit and Saleh (2000) describe the four elementary modes of behavior that explain the behavior of a complex system over time: growth, decay, growing oscillation and decaying oscillation. Eigenvalues are used to analyze changes in system behavior, with the real component of the eigenvalue representing growth or decay, and the imaginary component representing oscillation.

Sonification

Today's computing power creates a great number of opportunities for the field of sonification, particularly for interpreting multidimensional, complex data sets. An excellent source of information on the subject is a report prepared for the National Science Foundation by members of the International Community for Auditory Display (ICAD), who define sonification more completely as "the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation" (Kramer *et al*. 1997: 2). The Geiger counter is a well-known early example of a practical application of this technology. Sonification is now strongly endorsed as a valuable, engaging learning tool in education at all levels, particularly in the sciences. Flowers, Buhman, & Turnage (1996) provide evidence that most people can understand statistical data through the use of sound just as well as they can from reading graphs. Although much activity in sonification's parent field of audition is being devoted to spatial location, the present project leverages the advantage that auditory displays offer over visual ones by *not* focusing the learner's attention on a specific stimulus. This is a major reason why auditory displays are ideal for creating early warning systems (Belz *et al*. 1999).

ICAD also raises provocative issues in educational psychology. It highlights the need for methodological research with topics such as sonification's effectiveness, appropriateness, limitations and reliability in conveying information to the learner. ICAD also calls for "products that are portable across various platforms, flexible enough to allow for customization as well as default settings, and integrable with different kinds of data and software" (Kramer *et al*. 1997). The present project is intended as a small contribution toward establishing the field's methodology.

Prototype Methodology

We introduce sonified models for two simulations: a classic predator-prey model illustrating the interaction between hares and lynx populations, and a model illustrating how the number of cultured yeast cells grows until their alcohol byproduct becomes toxic. It must be emphasized that this work is a prototype and is not intended for evaluation as a polished interface. The prototype consists of data from Powersim imported and sonified by MAX and MSP software written in C. While other programs such as Pd (for Windows NT) and jMax (for Linux) are available, MAX and MSP performed quite well running at about 10% capacity on a 400 MHz Macintosh G4 for the for the 2-parameter model. For the eigenvalue model, processing usage was up to about 40%, due mainly to the rather CPU-intensive virtual spatialization unit used. In designing the prototype and especially the mapping of parameters from data to sound, careful attention was given to established principles in perception and cognition. While seemingly effective at expressing the data sonically and meaningfully, the choice of parameter mappings can be done in various ways, some of which may be more effective than others.

Despite these caveats, however, our work demonstrates that sonification in system dynamics is definitely possible and quite likely worthwhile. Everything represented visually has been captured sonically, and in the Alcohol and Cells model, we expressed 10 parameters of interest (the values and both 1^{st} and 2^{nd} order differences for both Alcohol and Cells variables, two eigenvalues, one imaginary value, and one ± sign) with just 4 sounds. The importing of data to the sonification environment was done with minimal adjustments, even though we moved from a Windows operating system to that of a Macintosh. Also, the interface originally developed for the single variable Hares is modular, so that now one can simultaneously view dynamic behavior for both Hares and Lynx, and subsequently, Alcohol and Cells, in identical formats. The Alcohol and Cells interface was then merely expanded to allow for eigenvalues.

To illustrate the creation and interpretation of sounds, we chose a classic two-parameter predator-prey model (Figure 1) involving Hares and Lynx. Kramer (1990) describes similar work planned but not completed. From preliminary findings, he postulated that realistic sounds may contribute to more vivid mental models but that abstract sounds may allow for different conceptualizations of the model. In our model, the two populations influence one another and oscillate indefinitely until a shock in the system, such as harvesting of a portion of the hares, is introduced. In converting the data to sound, decisions on parameter mapping and scaling must be made. We chose to express the range of data for each variable of interest with pitch, then scaled the maximum and minimum values between high and low pitches. While the user is free to alter pitch mappings and playback throughout the sonification, we chose to facilitate variable identification by creating default settings that keep the ranges separated. These are illustrated in Figures 2 and 3. In the event that the user chooses parameter settings that omit some of the data, an audio-visual "Out of Range" warning is given. Also, to maintain a simple look to the interface and to keep the harmonics of the upper range audible and well below the limiting Nyquist frequency, we chose to contain the entire fundamental frequency range for the model to between 65 Hz and 987 Hz (a continuous MIDI range of 36 to 84), or the approximate range of the human voice.

The complexity of the sound (Mathews 1999) was varied by mapping the absolute value of the first and second order differences to the musical parameters timbre and amplitude. The tones representing parameters were generated using additive synthesis with each tone consisting of eight partials. (The first partial is the same as the fundamental frequency, the second partial is the same as the first harmonic, and so on.) Roll off from one partial to the next was described as a constant ratio, with the constant being linearly dependent on the normalized absolute difference. A tone indicating a value with zero rate of change is comprised almost entirely of its fundamental (a roll off of -4 dB per partial), thus producing a dull sound, while tones representing values with high rates of change are comprised mostly of higher partials, (roll off up to + 4 dB), and thus sound bright and complex. The sum of the partial amplitudes was normalized so that changes in harmonic content do not influence overall amplitude. Instead, absolute and normalized second order differences were mapped to amplitude. Rather than using a one-to-one relationship between data samples and instant audio, sudden data spikes trigger an immediate increase in amplitude, followed by a quick decay, so that sudden shocks to the system such as harvesting of the hares are more easily perceived. This mapping also proved effective as an early warning detection, which in turn increases the prototype's attractiveness to Saleh and Davidsen's eigenvalue research. As they write of changes in loop dominance (Saleh and Davidsen 2000: 36):

> …such transitions typically constitute significant 'events' in the development of dynamic systems, events that we want to recognize, predict, prepare for, promote or postpone, cause or avoid. Our analysis can be generalized to any nth order model, and indicates that we may establish an 'early warning system' for such events, based on 'leading indicators', so as to be able to take appropriate actions in time.

The eigenvalue research brings us to our most complex sonification. Here we add distinct, separate notes to the layers of continuous sounds, giving the listener a powerful way of distinguishing behavior of the eigenvalues from that of the variables in the model, yet allowing the listener to sonically examine the simulation data and the eigenvalue data *simultaneously*. A model (Figure 4) illustrating the rise and fall of yeast cells as a function of the amount of alcohol they produce was chosen due to its simple structure and complex behavior (Myrtveit and Saleh 2000). It features only two state variables yet exhibits behavior in each of the four elementary modes: divergent, divergent oscillatory, convergent oscillatory, and convergent (Figure 5). At the beginning of the Alcohol and Cells sonified simulation, sounds for two eigenvalues at two different pitches are heard as triplets, representing dominance of divergent behavior in the model. As the values of the eigenvalues decrease and become negative, the listener hears their sound move from the left channel to the right. The moment the model's eigenvalues converge, an imaginary component is formed; likewise, the pitches merge and a new quality to the sound is introduced. As the (always positive) imaginary value in the Alcohol and Cell model increases, a reverberation becomes more pronounced. It adds an additional sonic dimension to the representation and the knowledgeable listener can quickly discern that the model's dominant behavior is oscillatory. When the model's dominant behavior becomes convergent-oscillatory, the eigenvalues become negative and the triplets give way to singular notes. Finally, when the model's dominant behavior becomes purely convergent, the imaginary value goes to zero (Figure 6), the reverb effect disappears and the eigenvalues separate again into two pitches.

The combination of sonification and system dynamics is interdisciplinary and should attract wide attention from the fields of business, education and music. While our efforts have primarily catered to the first two, we merely hint at applications to electronic music by noting the realm of stored instrument sounds that perhaps can be used to convert sonified data to more discrete and recognizable MIDI pitches.[iii] Limitations encountered include numerous crashes during development, most likely due to extreme values and unstable programming objects, and the inability to combine more than one graph in the same window. Also, since the frequency range for tonal hearing is amplitude dependent (Handel 1989), we found that at times the amount of overtones caused considerable change in perceived loudness and even pitch. This change in loudness was also true of the eigenvalues when they converged. Some tinkering with scaling is in order since complex sounds are more difficult to distinguish from one another, but it *is* possible in MAX and MSP to dynamically and automatically adjust volume to counteract perceived changes in loudness.

Reactions from listeners were encouraging but mixed: from finding the eigenvalue presentation extremely clear and useful, to never (throughout an hour-long presentation) feeling adept at interpreting the sounds, to wishing the sounds were less artificial and somehow more descriptive or realistic. Such varied responses to a completely unfamiliar form of analysis are to be expected. We reiterate that while this underdeveloped field is part art, part science, it offers both challenge and opportunity.

Future Research

Much work remains for sonification in system dynamics and it is hoped that the link to the eigenvalue research will strengthen as both concepts mature. Future considerations include better usage of sonic imaging, fuller use of available ranges for sonic parameters, a menu of choices for parameter mappings and scaling as well as visual displays, a link to a sortable library of stored sounds and a loop feature for repeated listening of temporal subsets of data. More interfaces must be developed, particularly ones for larger models. Controlled experiments must be conducted to shed light on issues such as optimal combinations of parameter mapping, sensitivity of auditory perception to quality of auditory equipment and listening environment, limits in dynamic complexity to auditory perception and comprehension, and the effects of training with the learning environment. Training is indeed a significant issue, as it has a considerable effect on being able to hear the components of patterns, and its effects may vary widely among listeners (Espinoza-Varas and Watson 1989). Howard and Ballas (1982) refer to skilled sonar operators by describing the potential benefits of training with auditory pattern recognition.

For researchers in the combined area of sonification and system dynamics, the paramount goal remains supporting the hypothesis that sonification improves one's ability to learn from a simulation model and, accordingly, improves decision making. It may be wise to treat the use and development of sonification as part art, part science, dabbling and progressing through experience. While some combinations of parameter mapping may be more effective, the best choice may depend on the type and complexity of the model, or on user preference, or perhaps even on experience with the sonification interface. Kramer, in stressing a phenomenological approach, offers the concept of “affective association…for example, a sound may get uglier as defoliation occurs in an ecosystem model” (1990: 270), as a methodological component to consider.

While research demonstrates the benefits of combining visual and auditory information to enhance understanding of complex systems (Bly 1982), ICAD points to ventriloquists as an admonition for the combination of aural and visual processing, explaining that while it may prove effective in learning, it may also create perceptual misconceptions (Kramer *et al*. 1997). Shepard reminds us of the possibly misleading interactions between the senses: “Without smelling it first, an apple is often indistinguishable in taste from an onion” (1999: 127). Walker and Brewster (2001) counter, however, that in human-computer environments such misconceptions can be overcome with on-screen zooming.

Conclusion

For the field of education, for managers and researchers working with massive databases, and for analysis of environments of considerable dynamic complexity, sonification should be considered along with system dynamics as a tool for learning, management and decision making. Creating a sonic overlay, so that the system data and the corresponding eigenvalues can be examined simultaneously, considerably enhances the power of the analysis. But awareness of sonification’s benefits and potential must increase. Kramer reveals the bias toward visual display embedded in our language by citing common phrases such as “off the charts” and “he’s at his peak”, and suggests that we promote such phrases as “internet rates are bright” or “inventory has a real thump to it” (1990: 272). Education seems a particularly ripe field for greater use of sonification and one wonders about parallels with other disciplines, such as the teaching of perception of motion pictures, or of phase changes in chemistry. Much work is to be done, however, to establish sonification as a common learning method.

Acknowledgements

The authors thank Pål Davidsen, professor of System Dynamics at the University of Bergen, for support of this project, and the digital art company BEK for the use of its facilities and equipment.

Appendix

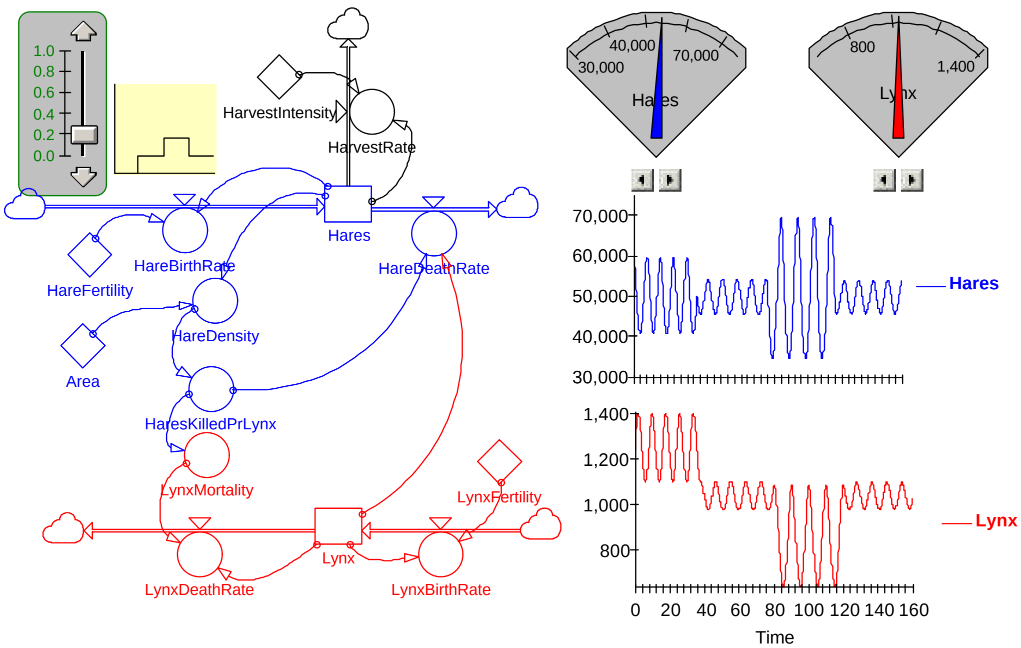

Figure 1: Powersim version of Hares and Lynx model with harvesting and visual displays

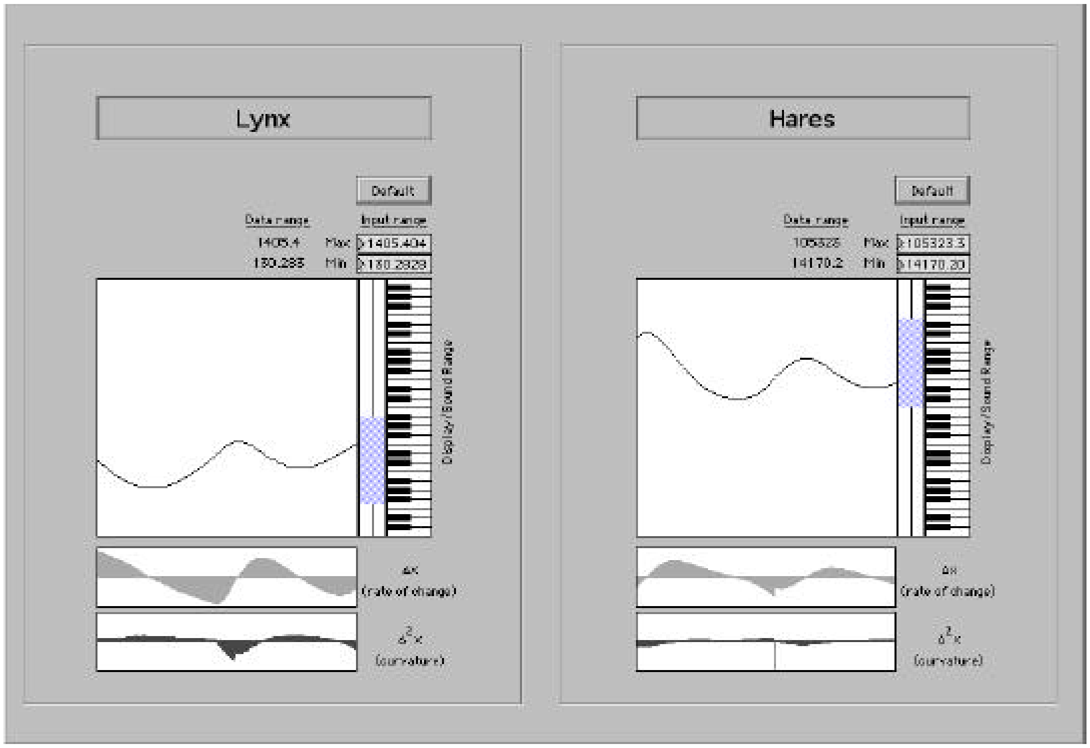

Figure 2: Sonification interface for Hares & Lynx model using MAX & MSP

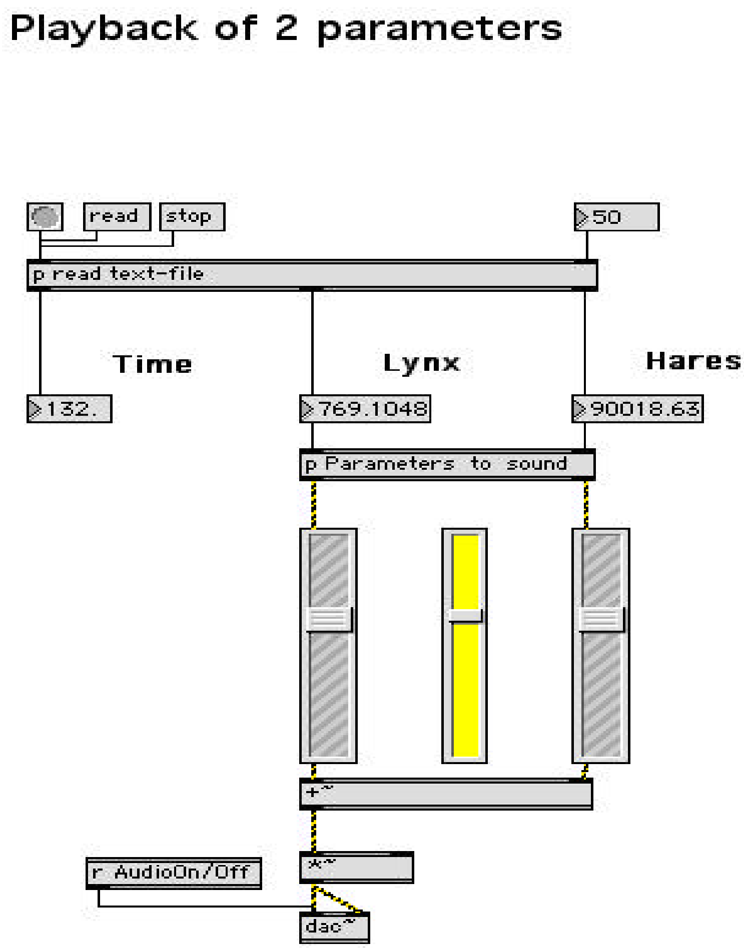

Figure 3: Sonification control for speed and volume

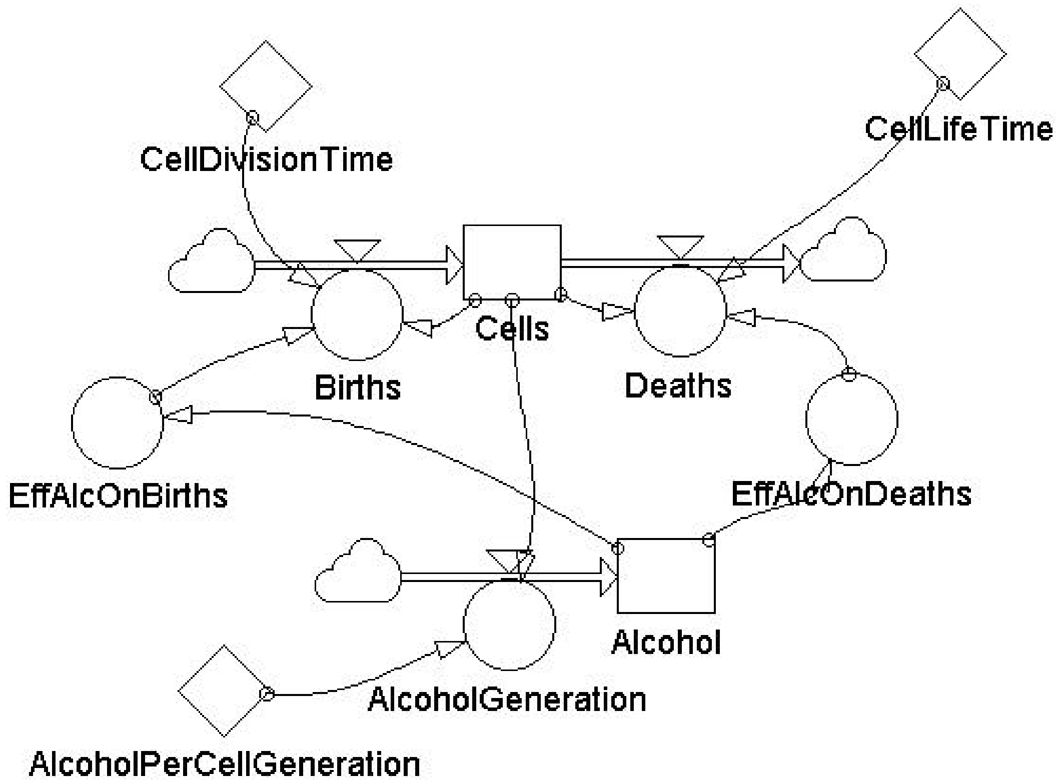

Figure 4: Powersim model of Alcohol & Cells

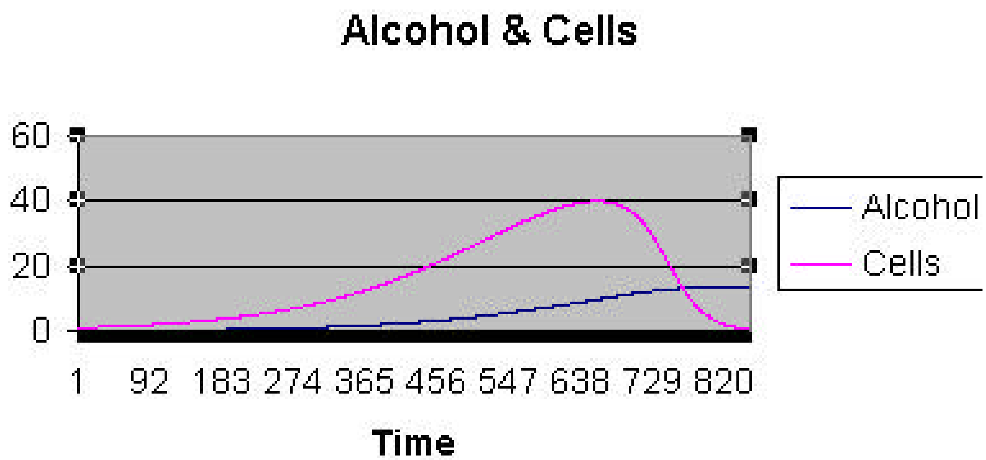

Figure 5: Graph of Alcohol & Cells

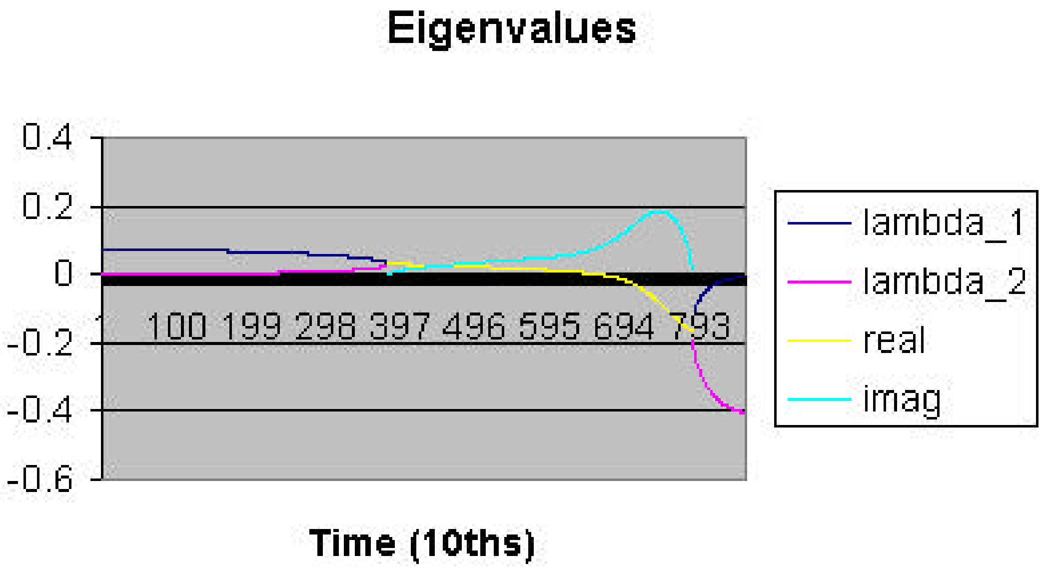

Figure 6: Graph of eigenvalues with their real and imaginary components for Alcohol & Cell model

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[i] The concept of beats may hold particular appeal to the system dynamics community in highlighting, for example, tiny yet critical disturbances to a system in apparent equilibrium. The emergence of beats in a tone can produce a dramatic perceptual effect.

[ii] Numerous models exist for categorizing learning styles, also known as cognitive styles or learning modalities.

[iii] In our presentation of the prototype, we did titillate the audience's imagination by including an auditory example of the pureness of the oscillating hares tone (at its peak) making a transition to the sound of a flute beginning Debussy's Prélude a l'après midi d'un faune. To pay tribute to the potential synthesis of such diverse fields, we have entitled our rendition Prélude a l'après MIDI d'un *lynx*.

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