1/F NOISE AND AUDITORY AESTHETICS: SONIFICATION OF A DRIVEN BEAD PILE

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ABSTRACT

"$1/f$ noise" describes the behavior of many naturally occurring complex dynamical systems over time. Perhaps more surprising than its ubiquity in nature is its prevalence in speech and especially music. Current research suggests that aspects of the human emotional response to music can be predicted using analysis based upon $1/f$ distributions. Musical compositions in which the pitch and duration of notes over time correspond to $1/f$ distributions have been found to be more pleasant than non-$1/f$ distributions. The current research compares the sonification of a driven bead pile to an experimentally contrived deviation. Preliminary results suggest that the findings of pitch and duration may be extended to timbre and spatialization. The benefits of continued research into the application $1/f$ distributions in sonification for the auditory display community are discussed.

1. INTRODUCTION AND MOTIVATION

1.1. Motivation

The idea that nature and proportion are fundamental to aesthetics stretches into antiquity. Themes of nature in art and music are not uncommon in the western tradition and appear in other traditions as well. Contemporary research and technology has opened the door for scientific perspectives on this relationship. Specifically, the evolving fields of auditory perception and music cognition coupled with the advent of powerful sound synthesis programs such as SuperCollider have made a rigorous and empirical methodology feasible. The core of the research agenda is the discovery of universal principles that can guide the compositional decisions for any auditory display.

1.2. $1/f$ Noise and Self-Organized Criticality (SOC)

The distributions of events in many physical processes varies as

$$P(f) = 1/f^{\alpha} \tag{1}$$

where $P(f)$ is the probability of an event f and the exponent α varies such that $0.5 \leq \alpha \leq 1.5$ over many decades [1]. The prevalence of this distribution in human ecology, speech and music is perhaps the most remarkable [2][3]. Informally, the law represents the proportion of certain events happening over time in a stochastic system. Examples of these events and distributions include earthquake magnitudes, extinctions of species, incomes, and traffic jams [4][5]. A chronological bibliography is maintained by http://www.nslij-genetics.org/wli/zipf/.

Self-Organized Criticality was initially proposed in 1987 as a general framework for understanding many instances of $1/f$ noise [6]. In the SOC paradigm, a myriad of independent systems related to one another by short range forces naturally organize themselves to a critical state defined by naturally occurring external conditions. At the critical state, these systems become complex and simple determinism is lost. The same minute perturbations can cause catastrophic changes or no change at all. However, the majority of events would be small and over time the probability $P(s)$ of events of size s would follow the power-law

$$P(f) = P_0 s^{-\tau}, \tag{2}$$

where $\tau = 1.5$ is the power law exponent of universal quality.

The current experiment sonifies the mass of a bead pile driven to a critical state by dropping single beads onto the apex at discrete time intervals. An example of the mass a driven bead pile over time is displayed in Fig. 1. Though the mass over time does not explicitly display a distribution consistent with (1), the size of the resulting avalanches over time is within the upper limit of α. The ideal avalanche size distribution is displayed in Fig. 2. A log-log plot reveals a straight line of slope -1.5. This behavior is exemplar of SOC.

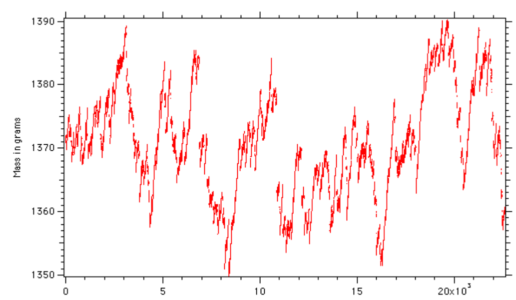

Figure 1: A graph of the mass of a driven bead pile at its critical angle of repose. This data run included in excess of 2×10^4 bead drops.

1.3. $1/f$ Noise in Auditory Display: "Pleasantness"

Following research published in 1975, Voss and Clarke proposed $1/f$ noise as a tool for creating music-like correlation and structure over a wide range of times. They generated "music" by storing $1/f$ data from the voltage fluctuations of a current-based transistor and applying it to a standard musical scale (pentatonic, major, or chromatic). The process was repeated and applied to the durations of the notes as well. Their music was tested using $1/f^0$, $1/f$, and $1/f^2$ sources. Following a period of two years of testing,

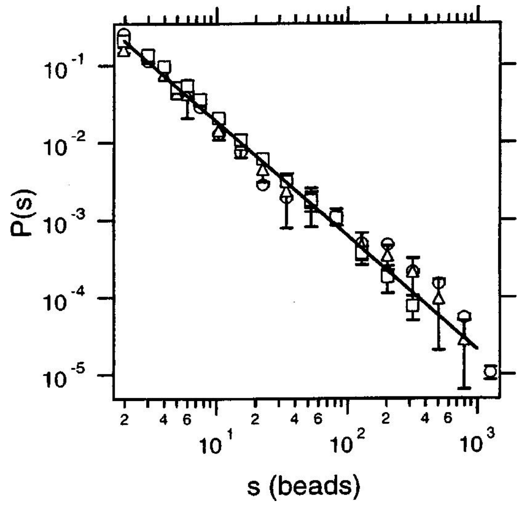

Figure 2: A graph displaying the probability $P(s)$ of an average avalanche size s in ideal circumstances. Smaller avalanches are much more common than larger avalanches. The slope of this line is -1.5 and indicates that a simple power law describes the data. Figure from [7].

hundreds of listeners from a variety of musical backgrounds consistently preferred $1/f$ distributions to $1/f^0$ ("too random") and $1/f^2$ noise ("too correlated") [1].

The discovery that $1/f$ distributions could yield pleasing sounding music followed the initial discovery that the pitch and loudness fluctuations of various radio stations, including classical, jazz/blues, rock, and news/talk exhibited $1/f$ behavior [2]. Research into the presence of $1/f$ distributions in music has culminated in an analysis technique which has been used effectively for author attribution, style identification, and "pleasantness" prediction in music [8].

From these results, it is clear that $1/f$ distributions are a critical component to a "pleasant" sounding piece. Although pitch, loudness, duration, and other musical parameters are important predictors of pleasantness, advanced auditory displays use spatialization and timbre effusively. The present sonification compares the sonification of an SOC system to an experimentally contrived deviation which corrupts the power law. The sonification incorporates spatialization and timbre.

2. SONIFICATION OF A DRIVEN BEAD PILE

Portions of this section are taken from [7].

In their initial paper, Bak, Tang, and Weisenfield introduced the driven sandpile as the paradigm of Self-Organized Criticality [6]. By dropping grains of sand onto the top of the sandpile, the pile naturally organizes itself to a critical state whereby small perturbations (such as the addition of a single grain of sand) can cause catastrophic events. The "events" of a driven sand pile are avalanches, and in ideal situations, the proportion of small avalanches to large avalanches is consistent with the probability function of (2) with $\tau = 1.5$. Because a real-life sandpile would be difficult to study in a lab, computer models and simulations are typical. Experimental results are rare, but usually use a consistent granular material such as beads.

The College of Wooster has been studying the dynamics of a driven bead pile for over a decade. Experiments have varied parameters such as the pattern of beads glued to the base, size or shape of the base, and the height at which each bead is dropped onto the pile. Past research [7] suggests that of these parameters, only the variation of drop height had any significant affect on the simple power law of (2). Variation in drop height is discussed in more detail in section 2.2

The present sonification features a comparison of data from a low drop height and high drop height. After discussing the apparatus, the experimental methods for deviating the power-law from (2) will be discussed. The sonification of these deviations may lead to new insights into human auditory perception and pose important questions for aesthetics in auditory display.

2.1. Apparatus

It is interesting to note that insofar the sonification comes from the mass over time of a driven bead pile, the sonification uses data from a natural process. Furthermore, the sonification provides sound to the way nature functions across a variety of critical systems. Although a computer simulation may be able to construct a virtual sandpile, listening to this data is qualitatively different.

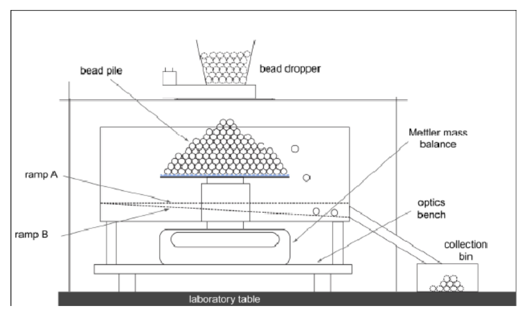

Figure 3: A diagram of the apparatus. The typical bead pile consists of approximately 15-17$\times10^3$ beads of 3mm diameter. The bead dropper can be raised or lowered to a desired height.

In the typical experiment, uniform, spherical glass beads form a conical, granular pile. The pile is built on a base of arbitrary size and shape with one layer of beads glued to the top so the beads can form a pile without slipping off when they are poured on. The base of the pile rests on an electronic balance, accurate to the nearest 0.01 gram. A pile consists of 15-17$\times10^3$ beads, making it an idealization of a sandpile.

A single bead is dropped from a bead dropper every 8 seconds. If there is a large avalanche, the dropper waits 30 seconds to incorporate aftershocks. As the beads are dropped, the scale measures the mass and sends the data to a computer running a LabVIEW program. An elaborate apparatus is constructed for catching and funneling the beads to the bead catcher when beads fall. To isolate the pile from external forces, the apparatus is placed in a plexiglass box and rests upon an optics table. The pile is so sensitive that even the smallest disturbance can create an unwanted artificial avalanche. A diagram of the apparatus is displayed in Fig. 3.

2.2. Deviating the Power Law

In ideal circumstances, the avalanche size distribution followed the simple power-law of (2) with $\tau = 1.5$ [7]. However, deviations to the straight power-law pose interesting questions for aesthetics. There are two ways to corrupt the ideal avalanche size distribution, both reflect changes in the way the pile dissipates energy.

One method involves increasing the drop height. By increasing the height that beads are dropped onto the pile, the pile must dissipate more energy per bead drop. The result is an increase in the number of avalanches, and a decrease in the average size of the avalanche. The number of large avalanches decreases drastically. The effect is demonstrated in Fig. 4. As the drop height increases further, the apex of the pile flattens completely. Although the value of τ changes little, an exponential function is added to the pure power law of (2) to account for the roll-off of τ at higher drop heights. Equation 2 becomes

$$P(s) = P_0 s^{-\tau} exp(-s/s_0), \tag{3}$$

where the parameter s_0 is a charachteristic avalanche size determined using a fitting function.

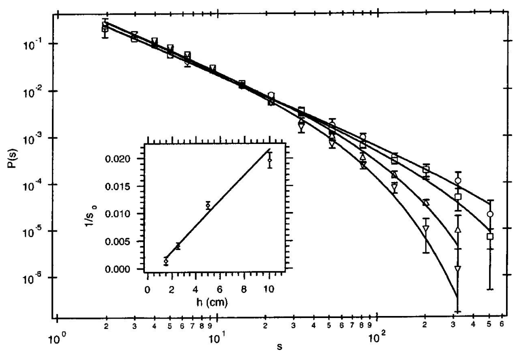

Figure 4: By raising the height at which beads are dropped onto the pile, the probability distribution deviates according to (3). This graph displays the avalanche size distribution of from drop heights of 1.5cm, 2.5cm, 5cm, and 10cm above the pile. The probability of large avalanches decreases dramatically with height. Figure from [7].

Whereas increasing the drop height creates a roll-off effect in the avalanche size distribution, using "sticky" beads creates a "hump." An avalanche size distribution which displays hump behavior is shown in Fig. 5. Humps in the avalanche size distribution where discovered accidentally through the use of "sticky" beads (i.e. beads that had not been washed properly). The effect is that the beads hold together tightly in the pile making avalanches less frequent but larger. The power-law is corrupted counter-intuitively: larger avalanches become more common than smaller avalanches. A characteristic equation to fit this behavior has not been determined. Associated with this deviation are sections of "quasi-periodic" large avalanches hidden in the mass over time data. The hump distribution provides a rich area for further research.

2.3. Sonification

The sonification uses the mass of the pile over time as in Fig. 1, not the avalanche sizes over time. The two data runs chosen for comparison were from drop heights of 1.5cm and 10cm. A comparison of the avalanche size distributions of 1.5cm and 10cm runs are displayed in the upper and lower curves of Fig. 4 respectively. Although these runs did not use glass beads, the effect of the avalanche size distribution was similar. For the sake of simplicity, the "sticky" runs were not sonified.

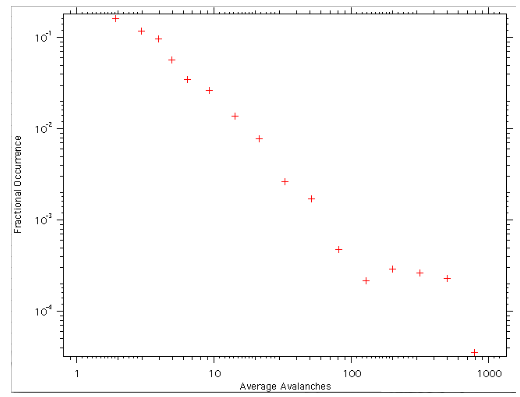

Figure 5: The avalanche size distribution of a driven bead pile with "sticky" beads. By increasing the restitution of the pile, larger avalanches become more probable than smaller avalanches. The mass of this pile over time has not been sonified, but poses interesting questions for further research.

A single data run can last 54 hours and include 18×10^3 bead drops whereas a sonification can be of arbitrary length. The data is one-dimensional and discrete: there is one mass reading for every bead dropped. Because of the sheer quantity data, it was thought best to present the sounds at the rate of 200 bead drops per second. This choice allowed a 54 hour run to be heard in approximately 90 seconds, but the current sonification includes about 12,000 bead drops and therefore lasts approximately 60 seconds. This speed emphasizes the presence of large avalanches, but a slower rate would give the hundreds of inaudible small avalanches more importance.

The sonification was created using SuperCollider 3 [10]. Although SuperCollider offers a variety of sound sythesis possibilities and control features, only a few were used. Bead drops occurred every 0.005 second and lasted for 0.04 seconds. The "blur" created by overlaping sounds gave the sonification an ambient quality which did not interfere with the display of large avalanches. The values for mass were mapped onto the spatialization, timbre, and pitch using the UGens 'Pan2', 'Formant', and the '.midicps' command respectively.

The 'Pan2' UGen mapped the mass values to spatialization such that high mass $\Rightarrow$ right stereo speaker. Within the 'Formant' Ugen, the formant frequency and bandwidth frequency both were mapped from 100 to 1000 Hz such that high mass $\Rightarrow$ high frequency. Within the 'Formant' UGen, the command '.midicps' was used to map the range of mass values onto the fundamental frequency based upon the MIDI cycles per second with high mass $\Rightarrow$ high frequency. The chosen MIDI range was 40-60 or in musical notation E2 to C4.

2.4. Analysis

In 1978, Voss and Clarke created a "music" from a source of $1/f$ noise by mapping the voltage fluctuations across a current-based transistor to pitch and duration [1]. There was not a correlation between their pitch and durations. Different sets of $1/f$ noise were mapped to each sound parameter. However, in the current experiment the different parameters are correlated, and the same set of mass over time data was assigned to each parameter for each sonification. This difference may be important, but was not explored.

Voss and Clarke also suggested that $1/f$ noise sources could be used to control various synthesizer inputs. This idea is manifest in the current sonification through the variation of timbre and spatialization in addition to pitch. Although the mass of the driven bead pile over time is not strictly $1/f$, it is stochastic and the probability of avalanches sizes over time follows a power-law with exponent near 1.5. The duration of each note was kept constant as well as the time between bead drops. The comparison of sonifications seem to verify that the pure power law of (2), is more pleasant than the modified power law of (3). Though the current work lacks robust psychological testing and connection to the neurophysical mechanism, they would be fundamental to further research.

3. EXPLORATIONS IN 1/F NOISE: TOWARDS A DEEPER AESTHETIC UNDERSTANDING

This research project began through the observation that a given data set sounded $better$ over a range of mapping techniques. The link with $1/f$ distributions and past research was discovered secondary. In the realm of sonification design, aesthetic and perceptual principles are inseparable. A sonification that sounds unpleasant may be judged as strange and esoteric, while a naturally pleasing sound will attract the listener, perhaps motivating understanding. The ubiquity of $1/f$ distributions in nature, human ecology, music, and speech is interesting, but the ability to predict the human emotional response of "pleasantness" adds a deeper level of meaning. This section discusses the benefits of research into $1/f$ distributions for the science of auditory display.

3.1. The Ideal Distribution

By programming a computer to measure the pitch and loudness fluctuations across radio stations, a nearly $1/f$ distribution was discovered [2]. The analysis technique used for author attribution, style identification, and "pleasantness" prediction found that 196 pieces from various genres exhibited an average distribution of approximately $1/f^{1.2}$ [11]. It has been shown that humans show aesthetic preference for images which display distributions between $1/f^{1.3}$ and $1/f^{1.5}$ [12]. There is also a connection between a distribution of $1/f^{1.4}$ and the golden ratio (0.61803...) [13].[8]

However complex the auditory parameters of a sonification or auditory display, there may be a fundamental organizational principle which will yield a naturally pleasant or aesthetically pleasing sound. A $1/f^0$ distribution sounds "too random," while a $1/f^2$ distribution is "too correlated." The combination of compositional control and adequate psychological testing may yield a range of values for α in (1), that are the most pleasing.

Distortions to the pure power law of (1) are common. In addition to finding the ideal value for the slope of this probability distribution of 1, a full understanding would include the aesthetic affects of these distortions. As discussed in section 2.2, there are ways of deviating the pure power law, making larger events relatively more or less common. What is the psychological effect of listening to these distortions? Are certain distortions more preferable than others, or even more preferable than the pure power law?

3.2. Timing, Spatialization, and Timbre

Sonifications and auditory displays typically use changes in pitch, duration, loudness, timing, spatialization, and timbre to convey information. $1/f$ distributions in pitch, duration, and loudness, have been shown to be more pleasant than non-$1/f$ distributions. Can these results be extended to include timing, spatialization, and timbre? Given the complexities involved with timbre, how would such testing be conducted? Through the isolation of these parameters, it may be proven that humans naturally prefer $1/f$ distributions in all auditory parameters independently. However, do similar results persist in their combination? Such research may yield an understanding of "aesthetic space" in auditory perception.

3.3. Sonification Toolkits

A number of sonification toolkits have been developed to provide platforms for work in sonification across fields and levels of expertise. A full but non-exhaustive list is available in section 2 of [14]. Insofar as design is flexible, there will be a variety of possibilities for sonification. The principles developed through research into $1/f$ distributions may provide valuable insights for the design of such software.

Specifically, a "pleasantness" algorithm similar to what was developed for music in [8] may guide a user to choices that will naturally yield a pleasant display. Using such an algorithm, a computer might "listen" to a sonification or auditory display and provide the user with a critique, guiding the compositional process. Such an algorithm could provide benefits field of computer assisted composition as well.

3.4. Possible Objection

Objection: *$1/f$ noise applies to a characteristic distribution of events over time in a stochastic system. Most sonifications or auditory displays will not use $1/f$-like data, occluding the benefits of this research.*

The "pleasantness" prediction as described in [8], applies to any piece of music. It is based upon a system of musical events which are ranked according to their frequency of occurrence. The corresponding distribution of events over time yields the $1/f$-type distribution. Similarly, although a sonification or auditory display does not necessarily deal with $1/f$ or even stochastic data, an algorithm based upon the frequency and proportion of auditory events might have the same benefit as [8].

4. CONCLUSIONS

A sonification that compared data from a driven bead-pile using spatialization, timbre, and pitch suggested a preference for the pure power-law of (2). Further research into stochastic systems which display near-$1/f$ distributions may provide useful insight into fundamental principles of auditory aesthetics. It may be possible to extended the documented preference for $1/f$ distributions in pitch, loudness, and duration, to spatialization, timing, and timbre. Discovering an ideal distribution for events in any auditory display would be useful in the design of sonification and sound synthesis software. Such research may have profound implications for aesthetics.

5. ACKNOWLEDGMENTS

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