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### '1/f noise' in music and speech

THE power spectrum  $S(f)$ , of many fluctuating physical variables,  $V(t)$ , is '1/f-like', varying as  $f^{-\gamma}$  ( $0.5 \leq \gamma \leq 1.5$ ), over many decades of frequency (see ref. 1 for review). We have found that loudness fluctuations in music and speech, and pitch (melody) fluctuations in music exhibit 1/f power spectra.

$S(f)$  is related to the autocorrelation function  $\langle V(t)V(t+\tau) \rangle$  by the Wiener-Khinchine relationships<sup>2</sup>. If  $V(t)$  can be characterised by a single correlation time  $\tau_c$ ,  $V(t)$  is correlated with  $V(t+\tau)$  for  $|\tau| < \tau_c$ , and is independent of  $V(t+\tau)$  for

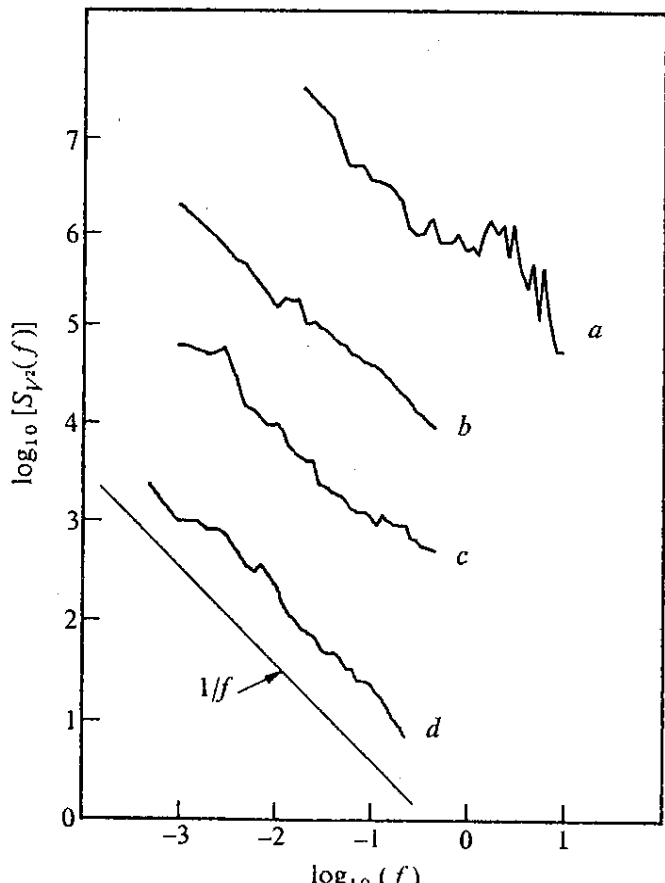


Fig. 2 Loudness fluctuation spectra,  $S_{V^2}(f)$  against  $f$  for: a, Scott Joplin Piano Rags; b, classical radio station; c, rock station; d, news and talk station.

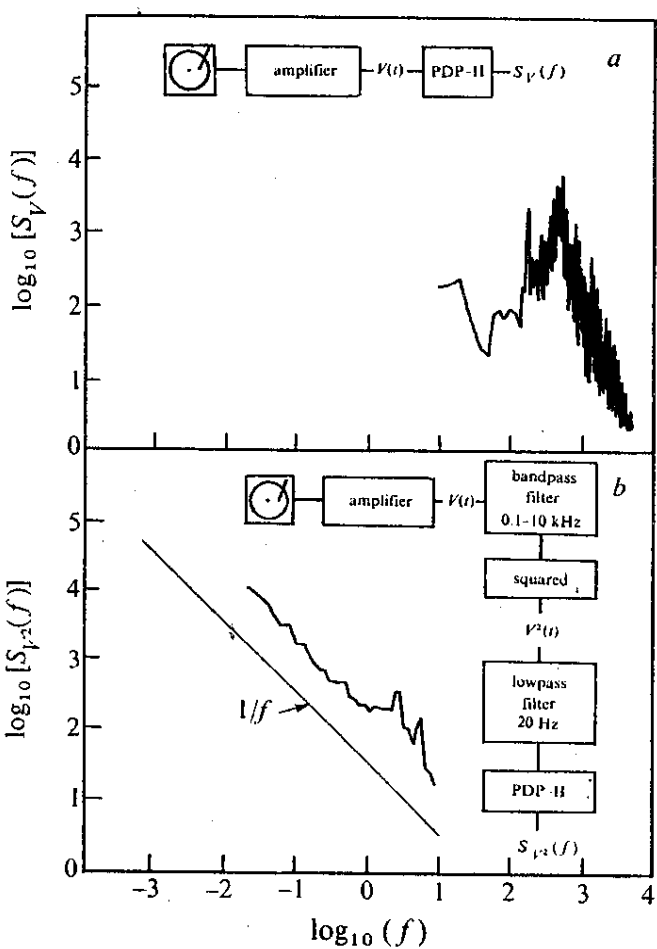


Fig. 1 Bach's 1st Brandenburg Concerto: a,  $S_V(f)$  against  $f$ ; b,  $S_{V^2}(f)$  against  $f$ .

$|\tau| > \tau_c$ . It can be shown that  $S(f)$  is 'white' for frequencies  $\ll 1/2\pi\tau_c$ , and is a rapidly decreasing function of frequency (usually  $f^{-2}$ ) for frequencies  $\gg 1/2\pi\tau_c$ . A quantity with a 1/f power spectrum cannot, therefore, be characterised by a single correlation time. In fact, the 1/f power spectrum implies some correlation in  $V(t)$  over all time scales corresponding to the frequency range for which  $S(f)$  is 1/f-like<sup>3</sup>. In general, a negative slope for  $S(f)$  implies some degree of correlation in  $V(t)$  over time scales of roughly  $1/2\pi f$ . A steep slope implies a higher degree of correlation than a shallow slope.

In our measurements on music and speech, the fluctuating quantity of interest was converted to a voltage whose power spectrum was measured by an interfaced PDP-11 computer using a fast Fourier transform algorithm. Our first measurements were on the output voltage,  $V(t)$ , of an audio amplifier. Figure 1a shows a log-log plot of the power spectrum,  $S_V(f)$ , of the audio signal from J. S. Bach's 1st Brandenburg Concerto averaged over the entire concerto. The spectrum consists of a series of sharp peaks in the frequency range 100 Hz-2 kHz corresponding to the individual notes in the concerto and, of course, is not 1/f-like. Although this spectrum contains much useful information, our primary interest is in more slowly varying quantities.

One such quantity is the loudness of the music. The audio signal,  $V(t)$ , was amplified and passed through a bandpass filter in the range 100 Hz-10 kHz. The filter output was squared and the audio frequencies filtered off to give a slowly varying signal,  $V^2(t)$ , proportional to the instantaneous loudness of the music. The power spectrum of the loudness fluctuations of the 1st Brandenburg Concerto,  $S_{V^2}(f)$ , averaged over the concerto is shown in Fig. 1b on a log-log plot. Below 1 Hz the spectrum is 1/f. The peaks between 1 and 10 Hz are due to the rhythmic structure of the music. Figure 2a shows the power spectrum of

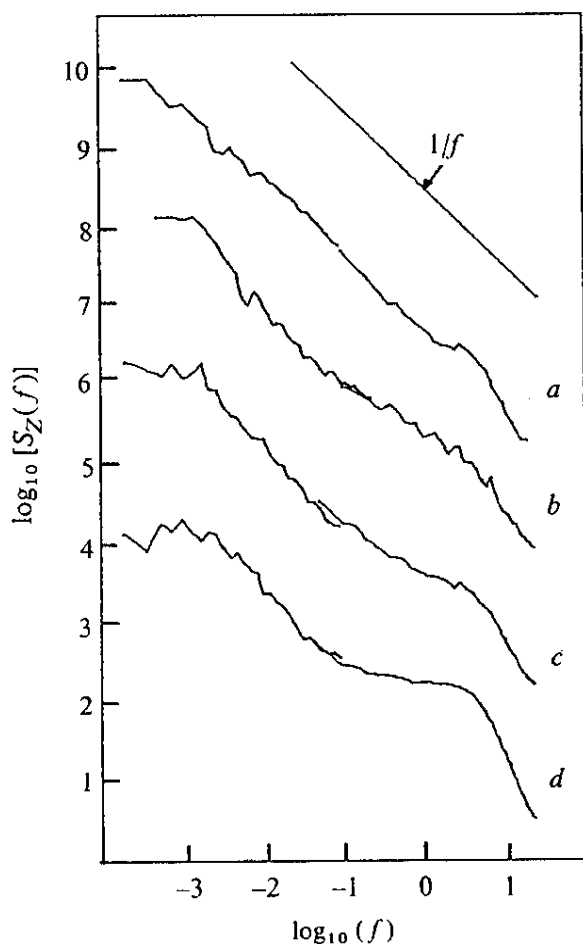


Fig. 3 Power spectra of pitch fluctuations,  $S_z(f)$  against  $f$ , for four radio stations: *a*, classical; *b*, jazz and blues; *c*, rock; *d*, news and talk.

loudness fluctuations for a recording of Scott Joplin Piano Rags averaged over the whole recording. Although this music has a more pronounced rhythm than the Brandenburg Concerto, and consequently has more structure in the spectrum between 1 and 10 Hz, the spectrum below 1 Hz is still  $1/f$ -like.

To measure  $S_v^2(f)$  down to even lower frequencies, we analysed the output from an a.m. radio.  $S_v^2(f)$  was averaged over approximately 12 h, and thus included many musical selections as well as announcements and commercials. Figure 2*b-d* shows the loudness fluctuation spectra for three different radio stations. Figure 2*b* shows  $S_v^2(f)$  for a classical station. The spectrum exhibits a smooth  $1/f$  dependence. Figure 2*c* shows  $S_v^2(f)$  for a rock station. The spectrum is  $1/f$ -like above  $2 \times 10^{-3}$  Hz, and flattens for lower frequencies, indicating that the correlation of the loudness fluctuations does not extend over time scales longer than a single selection, roughly 100 s. Figure 2*d* shows  $S_v^2(f)$  for a news and talk station, and is representative of  $S_v^2(f)$  for speech. Once again the spectrum is  $1/f$ -like. In Fig. 2*b* and *d*,  $S_v^2(f)$  remains  $1/f$ -like down to the lowest frequency measured,  $5 \times 10^{-4}$  Hz, implying correlations over time scales of at least 5 min. In the case of classical music this time is less than the average length of each composition.

Another slowly varying quantity in speech and music is the instantaneous pitch. A convenient means of measuring the pitch is by the rate,  $Z$ , of zero crossings of the audio signal,  $V(t)$ . For the case of music,  $Z(t)$  roughly follows the melody. Figure 3 shows the power spectra of the rate of zero crossings,  $S_z(f)$ , for four radio stations averaged over approximately 12 h. Figure 3*a* shows  $S_z(f)$  for a classical station. The power spectrum is closely  $1/f$ . Figure 3*b* and *c* shows  $S_z(f)$  for a jazz and blues station and a rock station. Here the spectra are

$1/f$ -like down to frequencies corresponding to the average selection length, and are flat at lower frequencies. Figure 3*d*, however, which shows  $S_z(f)$  for a news and talk station, exhibits a quite different spectrum. The spectrum is that of a quantity characterised by two correlation times: the average length of an individual speech sound, roughly 0.1 s, and the average length of time for which a given announcer talks, about 100 s. Communication, like most human activities, has correlations that extend over all time scales. For most musical selections the communication is through the melody and  $S_z(f)$  is  $1/f$ -like. On the other hand, for normal English speech the pitches of the individual speech sounds are uncorrelated: the ideas are not directly related to the pitches of syllables but rather to the meanings attached to them. As a result, the pitch power spectrum for speech is 'white' for frequencies less than about 3 Hz, and falls as  $1/f^2$  for  $f \geq 3$  Hz. In fact, in Fig. 3*a-c* one observes these speech shoulders which become more pronounced as the vocal content of the music increases or the commercial interruptions become more frequent.

The observation of  $1/f$ -like power spectra for various musical quantities also has implications for stochastic music composition. Most stochastic compositions are based on a random number generator (white noise source), which produces unrelated notes, or, on a low level Markov process, in which there is correlation over only a few successive notes. Neither of these techniques, however, approximates the  $1/f$  spectrum and the long time correlations reported here in music. We have used independent  $1/f$  noise sources in a simple algorithm to determine the duration (expressed as half, quarter, or eighth notes) and pitch (expressed in various standard scales) of successive notes of a melody. The music obtained by this method was judged by most listeners to be much more pleasing than that obtained using either a white noise source (which produced music that was 'too random') or a  $1/f^2$  noise source (which produced music that was 'too correlated'). Indeed, the sophistication of this ' $1/f$  music' (which was 'just right') extends far beyond what one might expect from such a simple algorithm, suggesting that a ' $1/f$  noise' (perhaps that in nerve membranes<sup>4</sup>) may have an essential role in the creative process.

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## Developmental changes in suckling of rat pups

ONTOGENETIC analysis of mammalian suckling provides a unique opportunity to observe the emergence of appetitive behaviour. Transitions in the nature of suckling may reveal progressive stages in the development of adult ingestive systems. Unfortunately, little information is available regarding the nature of suckling behaviour as it develops, and is eventually replaced by feeding and drinking, because it has proved difficult to separate the behaviour of the altricial infant from the contribution of the mother to the nursing dyad. We report here the developmental characteristics of, and changes in, the behaviour of suckling rats as they locate, apprehend and suckle the nipples of anaesthetised dams. This situation permits the detailed evaluation of rat pup behaviour in isolation from the active maternal role.