

# Self-organization in the Concert Hall: the Dynamics of Rhythmic Applause

An audience expresses appreciation for a good performance by the strength and nature of its applause. The initial thunder often turns into synchronized clapping - an event familiar to many who frequent concert halls. Synchronized clapping has a well defined scenario: the initial strong incoherent clapping is followed by a relatively sudden synchronization process, after which everybody claps simultaneously and periodically. This synchronization can disappear and reappear several times during the applause. The phenomenon is a delightful expression of social self-organization, that provides a human scale example of the synchronization processes observed in numerous systems in nature ranging from the synchronized flashing of the south-east Asian fireflies to oscillating chemical reactions [1–3].

Here we investigate the mechanism and the development of synchronized clapping by performing a series of measurements focused on both the collective aspects of the self-organization process as well as the behavior of the individuals in the audience. We recorded several theater and opera performances in Eastern Europe (Romania and Hungary) utilizing a microphone placed at the ceiling of the hall (Fig 1a). Typically, after a few seconds of random clapping a periodic signal develops (a signature of synchronized clapping), clearly visible in Fig. 1a as pronounced pikes in the signal. This transition is also captured by the order parameter (Fig. 1c), which increases as the periodic signal develops, and decreases as it disappears. While synchronization increases the strength of the signal at the moment of the clapping, it leads to a decrease in the average noise intensity in the room (see Fig. 1d). This is rather surprising, since one would expect that the driving force for synchronization is the desire of the audience to express its enthusiasm by increasing the average noise intensity. The origin of this conflict between the average noise and synchronization can be understood by correlating the global signal with the behavior of an individual in the audience. For this we recorded the local sound intensity in the vicinity of a group of individuals (Fig. 1b), unaware of the recording process. In the incoherent phase the local signal is periodic with a short

period corresponding to the fast clapping of an individual in the audience. However, the clapping period suddenly doubles at the beginning of the synchronized phase (approximately at 12s in Fig. 1a and b), and slowly decreases as synchronization is lost (Fig. 1e). Thus, the decrease in the average noise intensity is a consequence of the period doubling, since there is less clapping in unit time. An increase in the average noise intensity is possible only by decreasing the clapping period, which indeed does take place, as shown in Fig. 1e. However, the decreasing clapping period gradually brings the synchronized clapping back to the fast clapping observed in the early asynchronous phase, and synchronization disappears. Apparently, this conflicting desire of the audience to simultaneously increase the average noise intensity and to maintain synchronization leads to the sequence of appearing and disappearing synchronized regimes.

These results indicate that the transition from random to synchronized clapping is accompanied by a period doubling process. Next we argue that in fact period doubling is a necessary condition for synchronization. To address this question, we investigated the internal frequency of several individuals by controlled clapping experiments. Individual students, isolated in a room, were instructed to clap in the manner they usually do right after a good performance (Mode I clapping), or during the rhythmic applause (Mode II clapping). As Fig. 1f shows, the frequencies of the Mode I and Mode II clapping are clearly separated and the average period doubles from Mode I to Mode II clapping. Most important, however, we find that the width of the frequency distribution and the relative dispersion of the Mode II clapping is considerably smaller, a result that is reproducible for a single individual as well (Fig. 1g).

These results indicate that after an initial asynchronous phase, characterized by high frequency clapping (Mode I), the individuals synchronize by eliminating every second beat, suddenly shifting to a clapping mode with double period (Mode II) where dispersion is smaller. As shown by Winfree and Kuramoto, for a group of globally coupled oscillators the necessary condition for synchronization is that dispersion has to be smaller than a critical value [4,5]. Consequently, period doubling emerges as a condition of synchronization,

since it leads to slower clapping modes during which significantly smaller dispersion can be maintained. Thus our measurements offer a key insight into the mechanism of synchronized clapping: during fast clapping synchronization is not possible due to the large dispersion in the clapping frequencies. After period doubling, as Mode II clapping with small dispersion appears, synchronization can be and is achieved. However, as the audience gradually decreases the period to enhance the average noise intensity, it gradually slips back to the fast clapping mode with larger dispersion, destroying synchronization.

In summary, the individuals in the audience have to be aware that by doubling their clapping period they can achieve synchronization, which perhaps explains why in the smaller and culturally more homogeneous Eastern European communities synchronized clapping is a daily event, but it is only sporadically observed for the West and U.S. In general, our results offer evidence of a novel route to synchronization, not yet observed in physical or biological systems [2,3,5,6].

**Z. Nédá\***, **E. Ravasz\***, **Y. Brechet\*\***, **T. Vicsek\*\*\***, **A.-L. Barabási<sup>&</sup>**,

\* Babeş-Bolyai University, Department of Theoretical Physics, str. Kogălniceanu 1, RO-3400, Cluj-Napoca, Romania

\*\* ENSEEG-LTPCM, INP-Grenoble Saint-Martin D'Herès, CEDEX, France

\*\*\* Department of Biological Physics, Eötvös-Loránd University, Budapest, Hungary

<sup>&</sup> Department of Physics, University of Notre Dame, IN 46556, USA

**E-mail:** zneda@hera.ubbcluj.ro

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FIGURES

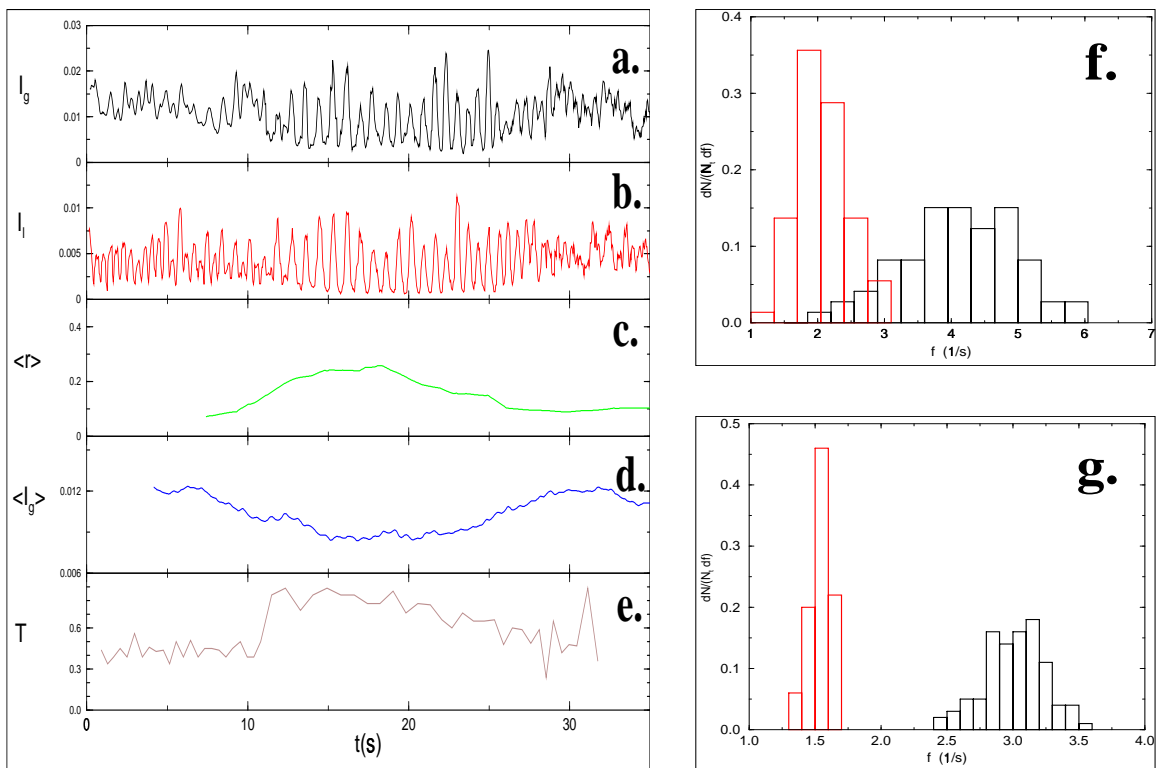


FIG. 1. Emergence of synchronization in clapping. (a) Global noise intensity as a function of time. The digitized data was squared and moving average was performed over a window of size  $0.2s$ , much smaller than the clapping period. The figure shows a characteristic region with the appearance and disappearance of the synchronized clapping. Over several performances we recorded 50 similar sequences of synchronized clapping. (b) Local noise intensity, measured by a hidden microphone in the vicinity of a spectator. (c) Order parameter,  $r$ , defined as the maximum of the normalized correlation between the signal  $c(t)$  and a harmonic function,  $r = \max_{(T,\phi)} \int_{t-T}^{t+T} c(t) \sin(2\pi/T + \phi) dt / \int_{t-T}^{t+T} c(t) dt$ , where  $\phi$  and  $T$  span all possible values. (d) Average noise intensity, obtained by taking a moving average over a  $3s$  window of the global noise intensity shown in (a). (e) The clapping period, defined as the intervals between the clearly distinguishable maxima. (f) The normalized histogram of clapping frequencies measured for 73 high school students (isolated from each other) for Mode I (black) and Mode II (red) clapping. (g) Normalized histogram for Mode I and II clapping obtained for a single student, sampled 100 times over a one week period.