Experimental study on dynamics of the multi-individual clapping interacting system

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Experimental study on dynamics of the multi-individual clapping interacting system

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Abstract Clapping synchronization in the concert hall is one of the paradigmatic phenomena in daily life. Though the multi-individual clapping system has been widely investigated for its rich dynamics, little is known about the interaction - a foundation of synchronization. The goal of this study is to uncover the dynamics underlying interaction by observing individuals synchronizing clapping rhythms. We find three coupling states in the multi-individual clapping process: local synchronization, complete synchronization, and complete desynchronization. The statistical analysis shows that the clapping rhythms of arbitrary two individuals in the system exhibit long-range cross-correlations, i.e., the next clapping beat to be played by one individual is dependent on the entire history of the system. Surprisingly, we find that the mean-field for the system with a small number of individuals ($N < 5$) is not necessary for the emergence of the synchronization process. To understand these findings, we propose a theoretical model for mutually inter-

acting individuals, which can well reproduce the statistical characteristics of the multi-individual clapping process and suggest a physiologically motivated explanation for the occurrence of the multi-individual clapping synchronization. Though this study provides an understanding about the fundamental characteristics of the multi-individual clapping interacting system, the statistical framework and theoretical model may also be applied to study the dynamics of other complex systems with multiple coupled oscillators.

Keywords Synchronization mechanism · Multi-individual clapping system · Dynamics · Clapping interaction

1 Introduction

The interaction between units has triggered a series of natural phenomena, such as synchronization [1], oscillatory death and pattern [2], explosive synchronization [3], chimera state [4], etc. The observation and discussion of interaction are critical in multi-oscillator systems. The mathematical frameworks to explain the coupled multi-oscillator system are based on the interaction between the oscillators. Pulselike coupling between oscillators is considered in the integrate-and-fire-type models [5]. Kuramoto and Winfree models [6] consider the interaction of globally coupled oscillators. Due to the complexity, experimental research on the interaction between oscillators in complex systems is much less than theoretical research.

Since 2000, the clapping system has been widely studied because of its simple experimental setups and operations. Néda et al. [7, 8] record the applause after many excellent theater and opera performances (in Romania and Hungary) by a microphone hanging from the concert hall ceiling. They find that the key to clapping synchronization is the period-doubling of the clapping rhythms and model the globally coupled two-mode stochastic oscillators to explain

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the causes of the emergence and disappearance of group clapping synchronization. Mann RP et al. [9] recruit 107 volunteers from the University of Leeds to participate in the clapping experiments, observe and record the time participants start and stop clapping, and then find that the beginning and end of clapping behavior are socially contagious. Michael Thomson et al. [10] select 33 university classes of varying sizes at St. Francis Xavier University for clapping experiments. In the experiments, each participant is instructed to clap together in synchrony following the signal of the researcher. Michael Thomson et al. record group applause in each class. They then find that the clapping frequency of the group in the synchronous state increases more quickly for a larger group size due to an asymmetric sensitivity in aural interactions. One limitation of the above experimental research is that group clapping synchronization is not quantified from the clapping behavior of each individual but rather described as a global phenomenon. The synchronization among a group is realized through the global output of the clapping system [7–16]. In this article, we examine the dynamics of the multi-individual clapping interaction. More specifically, we construct a multi-individual clapping system and collect for the first time individual-participant clapping recordings in the context of the undirected group. These results provide more objective evidence to the findings of clapping synchronization by calculating the pulse phase difference between arbitrary two individuals, which are not involved in previous studies on group clapping synchronization [7–16]. We show that the clapping rhythmic of arbitrary two individuals in the multi-individual clapping interacting system exhibit long-range cross-correlations (LRCCs), which appears to be a general phenomenon given that these LRCCs are found in all experimental performances. LRCC is a critical characteristic in the dynamics of the considered complex system. The LRCCs indicate that two series form a self-similar (fractal) structure [17]. Here, self-similarity implies that trends in the clapping periods are likely to repeat on different timescales, i.e., the fluctuation pattern of one individual's clapping period tends to be reproduced in a statistically similar manner at a later time-even in another individuals clapping period. The LRCCs exist widely in nonlinear coupling systems such as finance [18], transportation [19], climate [20], human behavior [21]. Note that LRCCs can be used to reveal strong anticipation in complex systems [22]. Thus, we infer that the multi-individual clapping interaction is a kind of strong anticipation. Strong anticipation is primarily introduced to account for the adaptation of (complex) organisms with their (complex) environment and had emerged as a new framework for studying prospective control [21]. The research on multi-individual clapping synchronization is of great significance to developing the human-computer interaction system [23]. In addition, the results of local cross-correlation anal-

ysis point out that the mean-field for a system with a small number of individuals ($N < 5$) is not necessary for the emergence of the synchronization process. The theoretical model we construct can well reproduce the dynamics of the multi-individual clapping interaction process and further uncover the synchronization mechanism underlying clapping interaction.

Although some recent studies on human behavior have explored the synchronization between individuals in the group [24,25], this is the first time to track the clapping dynamics of each individual and provide insights into the interaction of arbitrary two individuals in the context of group applause. Our statistical framework and theoretical model may also provide a new perspective for studying the group dynamics in other coupled multi-oscillator systems.

This paper is organized as follows. In Section. 2, we introduce the experimental setup and procedure. Section. 3 presents a metric to evaluate the global synchronization between individuals in a multi-individual clapping system. We present the dynamics of the multi-individual clapping interaction process in Section. 4. Then the theoretical model and the corresponding numerical simulations are presented in Section. 5. The conclusions and discussions are presented in Section. 6.

2 Experimental setup and procedure

Several students from Beijing Normal University volunteer for the studies. All participants have no known neurological injuries or musculoskeletal injuries in the upper limbs. The ethics committee of the School of Science, Beijing University of Posts and Telecommunications, approve the experiment prior to its realization. We obtain informed consent from all participants. The multi-individual clapping system we construct, the same as that in our previous study [26,27], consists of participants, radio devices, and recording devices. Participants' clapping dynamics are recorded by using condenser microphones (frequency response: 80-14000Hz, sensitivity: 73 ± 3 dB at 1000Hz), which are very light, cheap, and easily accessible to students. The microphones are connected to different personal computers with the Adobe Audition software, which simultaneously records the participants clapping signals in files. Each individual in the multi-individual clapping system has a set of recording devices and radio devices, so the clapping dynamics of each individual in the system can be recorded separately. Based on this, we can observe the interaction between individuals in the system. In the study, each recording typically lasts 30-40 seconds and contains 70-110 beats of clapping.

Several experiments are carried out to explore the multi-individual clapping interaction's dynamics.

Experiment I: Three-individual clapping interaction experiments. Thirty-six students from Beijing Normal Univer-

sity volunteer for the experiment. In this experiment, 36 participants are randomly arranged into 12 groups, with 3 participants in each group. In each group, 3 participants sit back-to-back in a chair and begin to clap simultaneously without the influences of other groups. The applause of each participant in a group is recorded separately with the microphone access to a computer.

Experiment II: Four-individual clapping interaction experiments. Forty-eight students from Beijing Normal University volunteer for the experiment. In this experiment, 48 participants are randomly arranged into 12 groups, with 4 participants in each group. In each group, 4 participants sit back-to-back in a chair and begin to clap simultaneously without the influences of other groups. The applause of each participant in a group is recorded separately with the microphone access to a computer.

3 Synchronization metric

Before describing the dynamics of the multi-individual clapping interaction in detail, we propose the metrics used in this work to evaluate the global synchronization between individuals in the multi-individual clapping interaction.

The temporal occurrences $t(1), t(2), \dots, t(n)$ of the beats are extracted from the recorded signals. $t_k(i)$ represents the i^{th} clapping moment of the participant k with $k=1, 2, \dots, N$, $i=1, 2, \dots, n$. $N=3, 4$ represents the total number of participants in each group. n represents the total number of clapping beats contained in each recording. The synchronization metric between individuals k and j in the group is defined as

$$\zeta_{kj} = \frac{D}{\frac{1}{n} \sum_{i=1}^n |t_k(i) - t_j(i)|}. \quad (1)$$

According to the Haas effect [28], when two sounds with equal intensity (one of which is delayed) reach the listeners ear with a time delay within $D = 0.03s$, the auditory cannot feel the presence of the delayed sound between the two sounds and then takes the two sounds as being originated from the same source. Therefore, $\zeta_{kj} \geq 1$ represents that the synchronized applause of participants k and j . The larger ζ_{kj} corresponds to higher global synchronization between participants k and j . In addition, the clapping period reads $q(i) = t(i) - t(i-1)$ with $t(0) = 0$. In this study, the clapping period series are used to analyze the statistical characteristics of the multi-individual clapping interaction.

4 Experimental results and discussion

4.1 The coupling states of the multi-individual clapping interaction

The first set of analyses examine the coupling states of the multi-individual clapping interaction by calculating the pulse phase difference between individuals. We define $\Delta\phi(i) = (\Delta t(i) \times 360) / ((q_A(i) + q_B(i)) / 2)$ degrees as the pulse phase differences between individuals A and B [26]. According to the Haas effect [28], we define $\Delta\phi^*(i) = (0.03 \times 360) / ((q_A(i) + q_B(i)) / 2)$ degrees as the threshold of pulse phase synchronization. When $|\Delta t(i)| < 0.03$, $|\Delta\phi(i)| < \Delta\phi^*(i)$, individuals A and B achieve pulse phase synchronization. In addition, we use ζ_{AB} to measure the global synchronization between individuals A and B .

Fig. 1 Participants 1, 2, and 3 are synchronizing their clapping beats: comparison of the representative example 1 of Experiment I (a)-(c) with the model (d)-(f). The pulse phase difference between participants 1 and 2 (a), 1 and 3 (b), 2 and 3 (c) vs. the sequence number of the clapping beats. The red lines represent the pulse phase differences, and the black dashed lines represent the pulse phase synchronization threshold of $\Delta\phi^*(i)$ and $-\Delta\phi^*(i)$, respectively. The initial conditions of the numerical simulation are as follows: $B_1(i) \sim N(0.0399, 0.0186^2)$, $B_2(i) \sim N(-0.0007, 0.0009^2)$, $B_3(i) \sim N(-0.0755, 0.0757^2)$, $n=80$, $a_{jk} = 0.1$, $S_{jk}(1) = 0$, $b_k = 1$, $q_k^*(i)$ simulated by the EARFIMA procedure with $d = 0.4$, $W = 0.8$, $\varepsilon_k \sim N(0, 1)$, $\delta_k = 0.02$.

In the multi-individual clapping interaction, we find three coupling states: complete desynchronization, local synchro-

Fig. 2 Participants 4, 5 and 6 are synchronizing their clapping beats: comparison of the representative example 2 of Experiment I (a)-(c) with the model (d)-(f). The pulse phase difference between participants 4 and 5 (a), 4 and 6 (b), 5 and 6 (c) vs. the sequence number of the clapping beats. The initial conditions of the numerical simulation are as follows: $B_1(i) \sim N(0.004, 0.002^2)$, $B_2(i) \sim N(0.003, 0.001^2)$, $B_3(i) \sim N(-0.08, 0.008^2)$, $a_{12} = a_{13} = 0.2$, $a_{21} = a_{23} = 0.03$, $a_{31} = a_{32} = 0.02$, the initial conditions of other parameters are consistent with those in Fig. 1.

nization, and complete synchronization. Fig. 1 (the representative example 1 of Experiment I) and Fig. 5 (the representative example 1 of Experiment II) show the complete desynchronization states. The absolute values of the pulse phase difference between participants are greater than $\Delta\phi^*(i)$ (Figs. 1(a)-(c) and Fig. 5). The synchronization metrics between participants are consistent with the above results. As shown in Fig. 4(a), $\zeta_{12}, \zeta_{13}, \zeta_{23}$ are far less than 1 in the three-individual clapping interaction. In the four-individual clapping interaction, $\zeta_{12}, \zeta_{13}, \zeta_{14}, \zeta_{23}, \zeta_{24}, \zeta_{34}$ are far less than 1 (Fig. 8(a)). These results indicate that the weak local synchronization between participants resulted in their poor global synchronization.

Fig. 2, Fig. 6, and Fig. 7 show the local synchronization states in the multi-individual clapping interaction. As shown in Fig. 2 (the representative example 2 of Experiment I), the pulse phase differences between participants 4 and 5 exhibit the oscillation with damped amplitude (red line in Fig. 2 (a)). As time is larger than a certain value (for example, 3^{th} and 9^{th} beat), the oscillating pulse phase difference $|\Delta\phi_{45}(i)|$ between participants 4 and 5 begins to

Fig. 3 Participants 7, 8 and 9 are synchronizing their clapping beats: comparison of the representative example 3 of Experiment I (a)-(c) with the model (d)-(f). The pulse phase difference between participants 7 and 8 (a), 7 and 9 (b), 8 and 9 (c) vs. the sequence number of the clapping beats. The initial conditions of the numerical simulation are as follows: $B_1(i) \sim N(0.004, 0.002^2)$, $B_2(i) \sim N(-0.001, 0.001^2)$, $B_3(i) \sim N(-0.008, 0.008^2)$, the initial conditions of other parameters are consistent with those in Fig. 1.

be less than the threshold $\Delta\phi_{45}^*(i)$. However, it may become larger than $\Delta\phi_{45}^*(i)$ again, which indicates that the clapping coupling state of participants 4 and 5 is an intermittent synchronization; that is, there is no strict phase locking between participants 4 and 5 [29]. It is worth noting that the phenomenon is unaccounted for in many other systems such as pendulum clocks [30] and metronome systems [31]. In addition, the pulse phase differences between the participants change between positive and negative values, which indicates that the interaction between individuals in the multi-individuals clapping system is a kind of pre-judgment mode. These results are similar to the dynamics of the two-individual clapping system [26]. Further analysis shows that the interaction process between participants 4 and 6 (or 5 and 6) exhibits complete desynchronization. As shown in Figs. 2(b)-(c), the absolute values of the pulse phase difference between participants 4 and 6 (or 5 and 6) are greater than $\Delta\phi^*(i)$. The four-individual clapping interaction presents richer dynamics compared with the three-individual clapping interaction. Fig. 6 (the representative example 2 of Experiment II) shows that the pulse phases of two individuals achieve synchronization, and others are not syn-

Fig. 4 Three participants are synchronizing their clapping beats (Experiment I): comparison of Experiment I (a), (c), (e) with the model (b), (d), (f). The synchronization metrics between arbitrary two participants for the representative example 1 (Fig. 1) in (a), the representative example 2 (Fig. 2) in (c), the representative example 3 (Fig. 3) in (e). (b), (d), (f) The numerical simulations of the three-individual clapping interaction in equation (3) correspond to the experimental observations in (a), (c), and (e), respectively. The initial conditions of the numerical simulation of the representative examples 1(b), 2(d), 3(f) are consistent with those in Fig. 1, Fig. 2, Fig. 3, respectively.

chronized. As shown in Fig. 6, participants 5 and 8 achieve the pulse phase synchronization. The pulse phase differences between participants 5 and 8 show the oscillation with damping amplitude (red line in Fig. 6 (c)). The absolute values of the pulse phase differences between participants 5 and 6, 5 and 7, 6 and 7, 6 and 8, 7 and 8 are greater than $\Delta\phi^*(i)$ (Fig. 6 (a)-(b), (d)-(f)). Fig. 7 (the representative example 3 of Experiment II) shows the pulse phase synchronization of three individuals in the four-individual clapping interaction. Participants 9 and 10 achieve the pulse phase synchronization at beats 8-11, 51-60, 62-65, 77-85, and 87-90. Participants 9 and 11 achieve the pulse phase synchronization at beats 1-3, 8-9, 14-22, 28-29, 37-47, 49-50, 64-65, and 77-79. Participants 10 and 11 achieve the pulse phase synchronization at beats 4-8, 10-12, and 64-78. Therefore, participants 9, 10, and 11 achieve the pulse phase synchronization at beats 64-65, and 77-78, while participant 12 leads participants 9, 10, and 11, the four-individuals clapping interaction achieve three-individuals synchronization. In contrast to the four-individuals clapping interaction, three-individuals clapping interaction exhibits a phenomenon of complete synchronization. As shown in Fig. 3 (the representative example 3 of Experiment I), participants 7 and 8 achieve the pulse phase synchronization at beats 32-33, 35-36, 60-62, 64-69, and 74-76. Participants 7 and 9 achieve the pulse phase synchronization at beats 29-33, 56-59, 61-62, 64-69, and 74-76. Participants 8 and 9 achieve the pulse phase synchronization at beats 2-10, 13-18, 20-24, 26-27, 31-34, 36-40, 43-44, 53-55, and 60-71. Therefore, participants 7, 8, and 9 achieve the pulse phase synchronization at beats 32-33, 61-62, and 64-

Fig. 5 The representative example 1 of the findings from a recording of participants 1, 2, 3, and 4 clapping in synchrony (Experiment II). The pulse phase difference between participants 1 and 2 (a), 1 and 3 (b), 1 and 4 (c), 2 and 3 (d), 2 and 4 (e), 3 and 4 (f) vs. the sequence number of the clapping beats.

69, the interaction process achieve complete synchronization. The synchronization metrics between participants are consistent with the above results (Figs. 4 (c), (e) and Figs. 8 (c), (e)). What stands out in Fig. 1 (Fig. 2, Fig. 5, and Fig. 6) is the pulse phase differences between participants exhibit always positive values (or negative values), which indicates that there is a leader-follower relationship.

Previous studies on the multi-individual clapping interaction are primarily from the global's viewpoint, and little attention has been paid to the interaction between individuals in the clapping system. For example, Z. Nédá et al. [7, 8, 11–13] apply the average sound intensity of group applause as a metric to judge the local synchronization of applause and employ the average sound intensity of group applause to explain the emergence and disappearance of the clapping synchronization. Compared to these previous experimental investigations, the study provides a novel contributions. We show the coupling states by calculating the pulse phase difference between individuals, which provide more objective descriptions to the emergence and disappearance of clapping synchronization.

Fig. 6 The representative example 2 of the findings from recording participants 5, 6, 7, and 8 clapping in synchrony (Experiment II). The pulse phase difference between participants 5 and 6 (a), 5 and 7 (b), 5 and 8 (c), 6 and 7 (d), 6 and 8 (e), 7 and 8 (f) vs. the sequence number of the clapping beats.

4.2 The statistical characteristics of the multi-individual clapping interaction

We introduce detrended cross-correlation analysis (DCCA) in order to analyze the correlations between clapping rhythms (Fig. 9(a)). DCCA has been proved to be used to analyze non-stationary signals in human behavior [21], climate [20], and stock market [32]. In DCCA method (see supplementary materials for detailed algorithm), the relationship between the detrended covariance $F_{DCCA}^2(s)$ and the window size s determine the relationship between two different time series. If $F_{DCCA}^2(s)$ follows the power law $F_{DCCA}^2(s) \sim s^{2\lambda}$ and $\lambda > 0.5$, LRCCs exist. On the contrary, $\lambda = 0.5$ manifests that LRCCs do not exist [21]. It should be noted that the analysis results obtained from DCCA [33] may be affected by the limitation of the total length of experimental data. Due to the strong correlation between DCCA and detrended fluctuation analysis (DFA) (see supplementary materials for detailed algorithm), the interpretation of λ is analogous with that of the DFA exponent α , and the errors of λ and the DFA exponent α are expected to be about the same. We estimate the error of λ by analyzing the error of α in a short time series. As shown in Fig. S1 (see supplementary materials), for a data set of the same size as ours, the DFA result of a

Fig. 7 The representative example 3 of the findings from recording participants 9, 10, 11, and 12 clapping in synchrony (Experiment II). The pulse phase difference between participants 9 and 10 (a), 9 and 11 (b), 9 and 12 (c), 10 and 11 (d), 10 and 12 (e), 11 and 12 (f) vs. the sequence number of the clapping beats.

time series with the scaling exponent $\alpha = 0.5$ is expected to have an SD of $\sim \pm 0.15$, which is consistent with the results of Ref. [33]. Thus, we estimate that for a time series of the same size as ours, the SD of $\lambda = 0.5$ is expected to be $\sim \pm 0.15$.

We show a representative example of the findings from a recording of multi-individual clapping in synchrony (Experiment I-II) in Figs. 9(a)-(b) and Figs. 10(a)-(b). Evidence of the LRCCs in the three-individual clapping interaction (Fig. 9(a)) is shown in Fig. 9(b). The DCCA exponent between q_A and q_B is $\lambda_1 = 1.05 > 0.5 \pm 0.15$. The DCCA exponent between q_A and q_C is $\lambda_2 = 1.32 > 0.5 \pm 0.15$. The DCCA exponent between q_B and q_C is $\lambda_3 = 1.53 > 0.5 \pm 0.15$. Similarly, the clapping rhythms of arbitrary two individuals in the representative example of four-individual clapping interaction exhibit LRCCs. As shown in Figs. 10(a)-(b), the six DCCA exponents are greater than 0.5 ± 0.15 (black lines). The next beat of one participant is generated based on all previous clapping periods of all participants in the multi-individual clapping system. The LRCCs are found in most of recordings (red circles in Fig. 9(e) and Fig. 10(e) in which all DCCA exponents are higher than 0.5 ± 0.15 , although the ζ between arbitrary two participants in each recording is dif-

Fig. 8 Four participants are synchronizing their clapping beats (Experiment II): comparison of experiments (a), (c), (e) with the model (b), (d), (f). The synchronization metrics between participants for the representative example 1 (Fig. 5) in (a), the representative example 2 (Fig. 6) in (c), the representative example 3 (Fig. 7) in (e). (b), (d), (f) The numerical simulations of the four-individual clapping interaction in equation (3) correspond to the experimental observations in (a), (c) and (e) respectively. (b) The initial conditions of the numerical simulation of the representative example 1 are as follows: $B_1(i) \sim N(0.00002, 0.00002^2)$, $B_2(i) \sim N(-0.0029, 0.0031^2)$, $B_3(i) \sim N(0.0389, 0.0381^2)$, $B_4(i) \sim N(-0.0028, 0.003^2)$, $n = 80$, $a_{12} = a_{21} = a_{41} = 0.01$, $a_{13} = a_{24} = 0.04$, $a_{14} = a_{31} = a_{34} = a_{43} = 0.03$, $a_{23} = a_{32} = a_{42} = 0.02$, $S_{jk}(1) = 0$, $b_k = 1$, $q_k^*(i)$ simulated by the EARFIMA procedure with $d = 0.4$, $W = 0.9$, $\epsilon_k \sim N(0, 1)$, $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.04$. (d) The initial conditions of the numerical simulation of the representative example 2 are as follows: $B_1(i) \sim N(-0.02, 0.001^2)$, $B_2(i) \sim N(0.04, 0.002^2)$, $B_3(i) \sim N(0.001, 0.001^2)$, $B_4(i) \sim N(0.002, 0.002^2)$, $a_{jk} = 0.01$, $\delta_k = 0.01$, the initial conditions of other parameters are consistent with those in (b). (f) The initial conditions of the numerical simulation of the representative example 3 are as follows: $B_1(i) \sim N(-0.0003, 0.001^2)$, $B_2(i) \sim N(-0.0002, 0.001^2)$, $B_3(i) \sim N(-0.0001, 0.001^2)$, $B_4(i) \sim N(0.02, 0.02^2)$, the initial conditions of other parameters are consistent with those in (d).

ferent when participants synchronize their clapping rhythms (Experiment I and II).

In previous studies, the discussions of LRCCs focus on the two interacting complex systems, and it is found that the LRCCs between behavioral rhythms originate from global matching in statistical structures of fluctuation in long time-scales between clapping individuals [21,27]. Therefore, we infer that the multi-individual clapping synchronization process may result from global matching. This result means that even though there is no local interaction between individuals in multi-individual clapping interaction, there may be LRCCs between individual clapping rhythms. We will further discuss the inference in the theoretical model.

Since DCCA can not exhibit the nature of local interactions, we apply the method of windowed detrended cross-correlation (WDCC, see the supplementary materials for the detailed algorithm) [34], which has been widely used recently, to explore the local cross-correlation structure of two

Fig. 9 Three participants A, B, and C are synchronizing their clapping beats: comparison of experiments (a)-(b) with the model (c)-(d). (a) The clapping periods of participants A (red curve), B (blue curve), and C (green curve) exhibit slowly varying trends. (b) Evidence of the LRCCs in the three-individual clapping interaction. (c)-(d) Model for $B_1(i) \sim N(0.001, 0.00002^2)$, $B_2(i) \sim N(0.0006, 0.05^2)$, $B_3(i) \sim N(0.0511, 0.0156^2)$, $n = 80$, $a_{12} = a_{32} = 0.3$, $a_{13} = a_{23} = 0.1$, $a_{21} = a_{31} = 0.2$, $S_{jk}(1) = 0$, $b_k = 1$, $q_k^*(i)$ simulated by the EARFIMA procedure with $d = 0.4$, $W = 0.9$, $\epsilon_k \sim N(0, 1)$, $\delta_k = 0.03$ predicts the DCCA exponents $\lambda > 0.5 \pm 0.15$, in excellent agreement with the experimental result. (e) Synchronization metric ζ vs. the DCCA exponent in the Experiment I and model. The model generates $NN = 12$ pairs of clapping period series with a length $n = 80$. The predicted DCCA exponents $\lambda > 0.5 \pm 0.15$ of the model (blue rhombuses) are in excellent agreement with the results of Experiment I (red circles).

time series. For arbitrary two clapping period series with a length of n (Fig. 11(a)), the cross-correlations of the short window with length L from lag -10 to lag 10 are calculated. Before calculating the cross-correlations, the data in each window is detrended in order to avoid detecting spurious cross-correlation due to the drift in the window (see Fig. S2 in the supplementary materials). Moreover, a significant correlation in the classical sense (i.e., based on the Bravais-Pearson's correlation test [35]) is difficult to find due to the WDCC uses a very narrow window L ($L = 15$ in this paper) and removes linear trends. Thus, we pay more attention to the symbols of the average WDCC coefficients compared with their statistical significance [35]. The two-tailed location t-tests is applied to test the signs of averaged coefficients by comparing the obtained values with zero.

Fig. 10 Four participants A, B, C, and D are synchronizing their clapping beats: comparison of experiments (a)-(b) with the model (c)-(d). (a) The clapping periods of participant A (black curve), B (red curve), C (blue curve), D (green curve) exhibit slowly varying trends. (b) Evidence of the LRCCs in the four-individuals clapping system. (c)-(d) Model for $B_1(i) \sim N(0.002, 0.00002^2)$, $B_2(i) \sim N(-0.003, 0.0003^2)$, $B_3(i) \sim N(-0.004, 0.0004^2)$, $B_4(i) \sim N(-0.0052, 0.004^2)$, $n = 80$, $a_{12} = a_{13} = a_{14} = a_{21} = a_{31} = a_{32} = a_{34} = a_{41} = 0.0002$, $a_{23} = a_{24} = a_{42} = a_{43} = 0.3$, $S_{jk}(1) = 0$, $b_k = 1$, $q_k^*(i)$ simulated by the EARFIMA procedure with $d = 0.4$, $W = 0.9$, $\varepsilon_k \sim N(0, 1)$, $\delta_k = 0.03$ predicts the DCCA exponents $\lambda > 0.5 \pm 0.15$, in excellent agreement with the experimental result. (e) Synchronization metric ζ vs. the DCCA exponent in the Experiment II and model. The model generates $NN = 12$ pairs of clapping period series with a length $n = 80$. The predicted DCCA exponents $\lambda > 0.5 \pm 0.15$ of the model (blue rhombuses) are in excellent agreement with the results of Experiment II (red circles).

Fig. 11(a) and Fig. 12(a) present the average WDCC between the clapping period series in Experiment I-II, respectively. Location t-tests show that the average lag 0, lag -1, and lag 1 WDCC between clapping period series are positive in Fig. 11(a). The average lag 0, lag 1 cross-correlations between clapping period series are positive in Fig. 12(a). These results prove that the multi-individual clapping synchronization seems to have emerged from mutual adaptation between individuals [21]; that is, the multi-individual clapping synchronization may come from the local interaction between clapping individuals which is consistent with the conclusions in the interpersonal interaction [21,35]. Therefore, we suggest that the multi-individual clapping synchronization may result from the global matching in statistical structures of fluctuation in long timescales between clap-

ping individuals and the local interaction between clapping individuals. We will further explore this hypothesis in the theoretical model.

Fig. 11 Average windowed detrended cross-correlation functions (from lag -10 to lag 10) between clapping period series ($NN = 12$) for Experiment I in (a) and model in (d). Average windowed detrended cross-correlation functions (from lag -10 to lag 10) between clapping period and coherent asynchrony ($NN = 12$) for Experiment I in (b) and model in (e). Average windowed detrended cross-correlation functions (from lag -10 to lag 10) between clapping period and noncoherent asynchrony ($NN = 12$) for Experiment I in (c) and model in (f). *: two-tailed location t-tests, $p < 0.01$.

The average lag 0 WDCC in the multi-individual interaction is positive, but lag 0 in the two-individual clapping interaction is negative [27]. Roume et al. [35] find that the level of cross-correlation between individual inherent period series strongly influences lag 0 WDCC. The lag 0 WDCC is positive for the higher cross-correlation levels and negative for the lower cross-correlation levels. We will further explore the factors affecting the lag 0 WDCC in the multi-individual clapping interaction by numerical simulations.

It should be noted that in the multi-individual clapping interaction, the WDCC could exhibit an asymmetry between lag -1 and lag 1 coefficient, revealing a leader/follower relationship between participants [35], which is consistent with the conclusion in the coupling states of multi-individual clapping interaction (Fig. 1, Fig. 2, Fig. 5, Fig. 6, Fig. 7).

Another variable that may play an essential role during the interaction process is asynchrony, defined as the time delay between a given event in one individual and that of the corresponding event in the other. Many studies suggest that synchronization with regular metronome occurs based on discrete correction of asynchronies [36]. Here, we dis-

Fig. 12 Average windowed detrended cross-correlation functions (from lag -10 to lag 10) between clapping period series ($NN = 12$) for Experiment II in (a) and model in (d). Average windowed detrended cross-correlation functions (from lag -10 to lag 10) between clapping period and coherent asynchrony series ($NN = 12$) for Experiment II in (b) and model in (e). Average windowed detrended cross-correlation functions (from lag -10 to lag 10) between clapping period and noncoherent asynchrony series ($NN = 12$) for Experiment II in (c) and model in (f). *: two-tailed location t-tests, $p < 0.01$.

cussed the local cross-correlation between clapping period and asynchrony in the process of multi-individual clapping interaction. In contrast to the asynchrony in the two-individual interaction [21,27], we divide the asynchrony in the multi-individual clapping interaction into two categories: coherent asynchrony and noncoherent asynchrony. Coherent asynchrony is defined as asynchrony series related to clapping rhythm, while noncoherent asynchrony is defined as asynchrony series unrelated to clapping rhythm. For example, the clapping period series in a three-individual clapping interaction are $q_A(i)$, $q_B(i)$, $q_C(i)$, respectively. Asynchronies are computed as the differences between the cumulated sums of $q_A(i)$ and $q_B(i)$ ($q_A(i)$ and $q_C(i)$, $q_B(i)$ and $q_C(i)$):

$$\begin{aligned} S_{AB}(i) &= -S_{BA}(i) = S_{AB}(0) + \sum_{o=1}^i q_A(o) - \sum_{o=1}^i q_B(o), \\ S_{AC}(i) &= -S_{CA}(i) = S_{AC}(0) + \sum_{o=1}^i q_A(o) - \sum_{o=1}^i q_C(o), \\ S_{BC}(i) &= -S_{CB}(i) = S_{BC}(0) + \sum_{o=1}^i q_B(o) - \sum_{o=1}^i q_C(o). \end{aligned} \quad (2)$$

Participant A's coherent asynchronies are $S_{AB}(i)$ and $S_{AC}(i)$, and noncoherent asynchrony is $S_{BC}(i)$. Participant B's coherent asynchronies are $S_{AB}(i)$ and $S_{BC}(i)$, and noncoherent asynchrony is $S_{AC}(i)$. Participant C's coherent asynchronies

are $S_{BC}(i)$ and $S_{AC}(i)$, and noncoherent asynchrony is $S_{AB}(i)$. We compute the WDCC between the clapping period and its coherent asynchrony, and the WDCC between the clapping period and its noncoherent asynchrony.

In Fig. 11(b) and Fig. 12(b), we present the WDCC between the clapping period and its coherent asynchrony. We find similar results for the two situations. In the process of multi-individual clapping interaction, there is a strong positive lag 0 WDCC between the clapping period and its coherent asynchrony. This result confirms that the current clapping period is based on the direct correction of the previous asynchrony [21]. The local cross-correlation between the clapping period and the coherent asynchrony may result in multi-individual clapping synchronization. This conclusion is consistent with that of interpersonal interaction [27, 21,36]. The analysis results of WDCC between the clapping period and its noncoherent asynchrony are shown in Fig. 11(c) and Fig. 12(c). There is no strong positive lag 0 WDCC between the period and its noncoherent asynchrony. Previous researches on the dynamics of group clapping propose that each individual in the clapping system received the mean-field of all individuals, which can be taken as imposing stochastic and periodical driving on each individual. The synchronization among individuals is realized through the global output of the clapping system [7–16]. This conclusion is not suitable for the multi-individual clapping system based on a few individuals. For a small number of clapping systems ($N < 5$), the mean-field is not necessary for the emergence of synchronization.

5 Theoretical model and the results of numerical simulations

5.1 Theoretical model

Our experimental results show that the multi-individual clapping synchronization process may result from the local interaction between clapping individuals and the more global matching between clapping individuals. This hypothesis is consistent with the conclusion of two interacting complex systems [27,35]. We observe three experimental results to support the hypothesis. First, the clapping rhythms of participants in multi-individual clapping systems exhibit LRCCs, and LRCCs may originate from global matching (Fig. 9 and Fig. 10), which is consistent with the third theoretical framework (complexity matching) to explain interpersonal coordination [35]. Second, the multi-individual clapping synchronization process may emerge from period-to-period influences (Fig. 11(a) and Fig. 12(a)). Third, the clapping synchronization processs current clapping period is based on the direct correction of the previous asynchrony (Fig. 11(b) and Fig. 12(b)). The second and third experimental results

are consistent with the first theoretical framework (information-processing approach) to explain interpersonal coordination [35]. Considering the above three results we observed in Experiment I-II, a mathematical model for simulating multi-individual interaction is constructed in Eq. (3) based on the method of combining asynchrony correction and global matching [35],

$$q_k(i+1) = q_k^*(i+1) + \sum_{j \neq k}^N a_{jk} S_{jk}(i) + b_k B_k(i+1), \quad (3)$$

where the oscillator is indexed by k , and N represents the total number of individuals in the clapping system ($N = 3, 4$ in this paper). $S_{jk}(i)$ is a coherent asynchrony between individuals k and j in the i^{th} clapping beat (see Eq. (2)). $0 < a_{jk} < 1$ is the correction coefficient of coherent asynchrony $S_{jk}(i)$. b_k represents the noise intensity. $B_k(i)$ is Gaussian-distributed noise term with mean value μ_k and standard deviation σ_k (the values of the mean and standard deviation refer to our previous research [26]). The inherent clapping period $q_k^*(i)$ is simulated by the extended version of autoregressive fractionally integrated moving average (EARFIMA) procedure (see Eq. (4)). Autoregressive fractionally integrated moving average (ARFIMA) has been proposed that generates two time series, which exhibit LRCCs [17]. EARFIMA can generate multiple time series, arbitrary two of which exhibit LRCCs (see Supplementary materials). Therefore, the two clapping period series $q_k(i)$ and $q_j(i)$ generated by the theoretical model are cross-correlated in nature, and the multi-individual clapping interaction generated by the theoretical model has the characteristic of global matching. The process is defined by Eq. (4) with weights $w_s(d) = d\Gamma(s-d)/\Gamma(1-d)\Gamma(s+1)$, Gaussian white noise $\epsilon_k \sim N(0, 1)$, and gamma function Γ . The coupling constant of inherent clapping period series is $W \in [0, 1]$. When $W = 1$, there is no interaction between $q_k^*(i)$ and $q_j^*(i)$. $U = 1/(N-1)$ represents the correction coefficient of the coupling constant W . δ_k represents the strength of these noise components. d is a parameter in the range of $[-0.5, 0.5]$. d is related to the DFA exponent by $\alpha = d + 0.5$.

$$Q_k(i) = \sum_{s=1}^{\infty} w_s(d) q_k^*(i-s), \quad (4)$$

$$q_k^*(i) = W Q_k(i) + U(1-W) \sum_{j \neq k}^N Q_j(i) + \delta_k \epsilon_k.$$

5.2 The results of numerical simulations

When this individual rhythmic behavior is embedded within the collective, additional complexity arises because other

individuals are presumably providing some rhythmic stimuli. For example, there is local synchronization in multi-individual interaction, positive lag 0 cross-correlations between clapping rhythms, and a weak correlation between clapping rhythms and noncoherent asynchronies. These characteristics will not appear in interpersonal interaction [21, 35]. Therefore, the extent to which the theoretical model based on interpersonal coordination theory is suitable for the multi-individual clapping interaction process is unclear. Next, we verify the correctness of the theoretical model and explain the dynamics of the multi-individual clapping interaction.

Fig. 13 The numerical simulation of the four-individual clapping interaction in equation (3) corresponds to the experimental observations in Fig. 5. (a)-(f) The pulse phase differences vs. the sequence number of the clapping beats. The initial conditions of numerical simulation are consistent with those in Fig. 8(b).

5.2.1 The numerical simulations of the coupling states of the multi-individual clapping interaction

Figs. 1(d)-(f) and Fig. 13 show the numerical simulations of the complete desynchronization state. The absolute value of pulse phase difference between individuals is greater than $\Delta\phi^*(i)$. The synchronization metrics between the clapping of individuals simulated by the theoretical model are consistent with the above results (Fig. 4(b), Fig. 8(b)).

Fig. 14 The numerical simulation of the four-individual clapping interaction in equation (3) corresponds to the experimental observations in Fig. 6. (a)-(f) The pulse phase differences vs. the sequence number of the clapping beats. The initial conditions of numerical simulation are consistent with those in Fig. 8(d).

Figs. 2(d)-(f), Fig. 14, and Fig. 15 show the numerical simulations of the local synchronization. The clapping pulse phase differences between individuals 4 and 5 show the oscillation with damped amplitude in the numerical simulation of the three-individual clapping interaction (red line in Fig. 2(d)). The absolute values of the pulse phase difference between individuals 4 and 6, 5 and 6 are greater than $\Delta\phi^*(i)$ (the red line in Figs. 2(e)-(f)). Fig. 14 and Fig. 15 show the numerical simulations of the local synchronization state in the four-individual interaction. Fig. 14 shows the numerical simulations that the pulse phases of two individuals achieve synchronization and others are not synchronized. As shown in Fig. 14, individuals 7 and 8 achieve the synchronization of the pulse phase. The differences of the pulse phase between individuals 7 and 8 show the oscillation with damping amplitude (red line in Fig. 14(f)). The absolute values of the pulse phase differences between individuals 5 and 6, 5 and 7, 5 and 8, 6 and 7, 6 and 8 are greater than $\Delta\phi^*(i)$ (Figs. 14(a)-(e)). Fig. 15 shows the numerical simulations of the pulse phase synchronization of three individuals in the four-individuals clapping interaction. Individuals 9 and 10 achieve the synchronization of the pulse phase at beats 1-13, 15-22, 24-30, 40-43, 45-49, 58-62, and 71-73. Individuals 9 and 11 achieve the synchronization of the

pulse phase at beats 4-8, 17-18, 30-59, and 72-73. Individuals 10 and 11 achieve the synchronization of the pulse phase at beats 4-6, 15-17, 32-33, 35-43, 47-49, 63-68, and 70-78. Individual 12 leads individuals 9, 10, and 11. Therefore, individuals 9, 10, and 11 achieve the synchronization of the pulse phase at beats 4-6, 40-43, 47-49, and 72-73; that is, the numerical simulations of the four-individual clapping system achieve three-individual synchronization. Figs. 3(d)-(f) show the numerical simulations of complete synchronization in the three-individual clapping system. As shown in Figs. 3(d)-(f), individuals 7 and 8 achieve the synchronization of the pulse phase at beats 1-2, 10-14, 16-20, 23-25, 27-30, 37-40, 42-47, 49-50, 52-53, 61-70, and 73-79. Individuals 7 and 9 achieve the synchronization of the pulse phase at beats 5-6, 18-19, 23-25, 39-40, 42-47, 51-52, 56-57, 60-64, and 74-76. Individuals 8 and 9 achieve the synchronization of the pulse phase at beats 3-4, 6-9, 11-12, 14-15, 20-26, 30-33, 35-36, 39-41, 43-48, 52-64, 68-69, and 71-76. Therefore, individuals 7, 8, and 9 achieve the synchronization of the pulse phase at beats 23-25, 39-40, 43-47, 61-64, 74-76; that is, the numerical simulations of the three-individual clapping system achieved complete synchronization. The synchronization metrics between individuals are consistent with the above results (Figs. 4(d),(f) and Figs. 11(d),(f)). These results are consistent with the coupling states observed in the experiments (Figs. 1(a)-(c), Figs. 2(a)-(c), Figs. 3(d)-(f), Fig. 5, Fig. 6, and Fig. 7). Our theoretical model can well simulate the coupling states of multi-individual clapping interaction.

5.2.2 The numerical simulations of the statistical characteristics of the multi-individual clapping interaction

We generate 12 groups of three-individual clapping process and four-individual clapping process by the theoretical model, respectively. All the numerical simulations of the theoretical model are done on these 24 groups of clapping process. The clapping period series of arbitrary two individuals in the multi-individual clapping process simulated by the theoretical model exhibit LRCCs even though the synchronization metrics are different, consistent with the experimental results. As shown in Fig. 9(d), Fig. 10(d), the blue rhombuses of Fig. 9(e), Fig. 10(e), the most predicted DCCA exponents $\lambda > 0.5 \pm 0.15$ by the theoretical model are consistent with the Experiment I-II (Figs. 9(a)-(b), Fig. 10(a)-(b), red circles of Fig. 9(e) and Fig. 10(e)).

Consistent with the experimental observations (Fig. 11(a) and Fig. 12(a)), there is a positive lag -1 (lag 1) WDCC between clapping period series simulated by the model (Fig. 11(d) and Fig. 12(d)). There are significant positive lag 0 WDCC between the clapping period and its coherent asynchrony simulated by the model (Fig. 11(e) and Fig. 12(e)), which is consistent with the experimental observations (Figs. 11(b)

Fig. 15 The numerical simulation of the four-individual clapping interaction in equation (3) corresponds to the experimental observations in Fig. 7. (a)-(f) The pulse phase differences vs. the sequence number of the clapping beats. The initial conditions of numerical simulation are consistent with those in Fig. 8(f).

and 12(b)). In addition, there is no significant positive lag 0 WDCC between the numerically simulated clapping period and the noncoherent asynchrony (Fig. 11(f) and Fig. 12(f)), which is consistent with the experimental observations (Fig. 11(c) and Fig. 12(c)).

The model based on combining asynchrony correction and global matching can completely reproduce the dynamics of the multi-individual clapping interaction. The conclusion proves theoretically that the generation of multi-individual clapping synchronization process needs to consider both local interaction and global matching, which is consistent with the conclusion of interpersonal interaction. Previous studies on the theoretical framework for explaining the multi-individual clapping process are primarily from the mean-field perspective [7–16], ignoring the interaction between individuals in the clapping system. However, our simulations show that the theoretical model without the mean-field term can describe the experimental observations completely. This conclusion implies that the mean-field is not necessary for the clapping systems of small individuals ($N < 5$), which is the most critical point in our work on multi-individual clapping synchronization processes.

5.3 The parameter analysis

The results of the local cross-correlation show that the lag 0 WDCC between the clapping rhythms is positive, while the WDCC is negative in the two-individual interacting process [21,27,35]. Roume et al. [35] propose that the coupling strength (W) between the individual inherent behavior rhythms in two interacting complex systems is the main factor affecting the lag 0 cross-correlation. W is the main factor affecting the local correlation structure in the two interacting complex systems. However, the main factors affecting the structure of local cross-correlation in the multi-individuals interaction remain unclear.

Fig. 16 The WDCC of the numerical simulation in the correction coefficient of coherent asynchrony a_{jk} versus the coupling constant W . The red (blue) dots represent that the lag-0 WDCC coefficients are positive (negative). The initial conditions of the numerical simulation for the three-individual clapping system (a) are as follows: each a_{jk} has the same value and a_{jk} ranges from 0 to 0.25, $B_1(i) \sim N(0.004, 0.002^2)$, $B_2(i) \sim N(-0.001, 0.01^2)$, $B_3(i) \sim N(0.008, 0.008^2)$, $n = 80$, $S_{jk}(1) = 0$, $b_k = 1$, $q_k^*(i)$ simulated by the ARFIMA procedure with $d = 0.4$, $W \sim [0.1, 1]$, $\epsilon_k \sim N(0, 1)$, $\delta_k = 0.04$. The initial conditions of the numerical simulation for the four-individual clapping system (b) are as follows: each a_{jk} has the same value and a_{jk} ranges from 0 to 0.25, $B_1(i) \sim N(-0.04, 0.04^2)$, $B_2(i) \sim N(0.05, 0.04^2)$, $B_3(i) \sim N(-0.03, 0.04^2)$, $B_4(i) \sim N(0.07, 0.04^2)$, $n = 80$, $S_{jk}(1) = 0$, $b_k = 1$, $n = 80$, $q_k^*(i)$ simulated by the EARFIMA procedure with $d = 0.4$, $W \sim [0.1, 1]$, $\epsilon_k \sim N(0, 1)$, $\delta_1 = 0.04$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.01$.

Here we discuss this problem by analyzing parameter space $a_{jk} - W$, and the analysis results are shown in Fig. 16. We find that the positive lag 0 WDCC (red dot in Fig. 16) is distributed in all values of W . The coupling strength W between inherent period series is not the main factor affecting the positive lag 0 WDCC in the multi-individual clapping interaction. In contrast, the positive lag 0 WDCC only appears when $0 \leq a_{jk} \leq 0.2$. Obviously, in the multi-individual clapping interaction, the main factor influencing the lag 0 WDCC is a_{jk} . The main factor affecting the local cross-

correlation structure is a_{jk} . Therefore, we conclude that synchronization may be dominated by local interaction between individuals in multi-individual clapping interaction.

6 The conclusions and discussions

Understanding the interactions between individuals in the groups is becoming a central issue in the social and natural sciences, especially synchronization. Most of the previous studies on collective behavior in complex systems are from the global perspective, and the mean-field of all individuals drives the emergence of synchronization. There is a lack of observation and analysis about the interaction between individuals. Here, we attempt to track the dynamics of individual clapping in the multi-individual clapping interaction. First, we find three coupling states: local synchronization, complete synchronization, and complete desynchronization by calculating the pulse phase difference between arbitrary two individuals in multi-individual clapping system. In previous experimental studies on collective synchronization, it is difficult to observe the interaction between individuals in the group clapping system [7–16]. Thus, the coupling states between individuals are rarely involved. Our observations on the dynamics of multi-individual clapping interaction provide a new idea for the study of group synchronization. Second, the clapping rhythms of arbitrary two individuals in the multi-individual clapping process exhibit long-range cross-correlations (LRCCs); the multi-individual clapping process is a strong anticipation process. This conclusion provides new support for studying the origin of strong anticipation processes in complex systems with multiple coupled oscillators. Third, the nonsignificant lag 0 cross-correlations between the clapping period and the noncoherent asynchrony indicate that the influence of the mean-field in the multi-individual clapping interaction is negligible; that is, the mean-field is not necessary for the emergence of synchronization in the clapping system with few individuals ($N < 5$). Based on the statistical characteristics of the multi-individual clapping interaction, a theoretical model is constructed, which can well reproduce the dynamics of the multi-individual clapping process and reveal the synchronization mechanism of the multi-individual clapping system: both local interaction and global matching. This synchronization mechanism may vividly explain collective behaviors in group sensing movement and interpersonal coordination.

Beyond clapping behavior, the study has application in understanding other rhythmic human behaviors, such as walking, music, tapping, dancing. More broadly, explaining the interaction between individuals in multi-individual systems is of primary importance to understanding complex systems. Our theory framework based on experimental observations will be essential to reveal complex systems.

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Data Availability Since the website to which the experimental data will be uploaded has not been determined, the datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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