Social and nonlinear dynamics unite: Musical group synchrony

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Synchronization, the human tendency to align behaviors in time with others, is necessary for many survival skills. The ability to synchronize actions with rhythmic (predictable) sound patterns is especially well developed in music making. Recent models of synchrony in musical ensembles rely on pairwise comparisons between group members. This pairwise approach to synchrony has hampered theory development, given current findings from social dynamics indicating shifts in members' influence within larger groups. We draw on social theory and nonlinear dynamics to argue that emergent properties and novel roles arise in musical group synchrony that differ from individual or pairwise behaviors. This transformational shift in defining synchrony sheds light on successful out- comes as well as on disruptions that cause negative behavioral outcomes.

Musical synchrony in group behaviors

Human synchronization in groups occurs when individuals align a sequence of behaviors simultaneously in time with others. Distinct from mimicry or social mirroring behaviors, group synchrony refers to the fine-grained temporal relationships between each group member's sequence of actions (e.g., the production of musical tones) that show fast adaptation to other group members' actions. Synchronization arises not only in intentionally coordinated groups such as rowing teams or military parade marchers but also in unintentional situations such as walkers' gait [1], spectators' chants [2], or listeners' body sway in response to music [3,4] or to speech [5]. Synchrony arises in many group contexts; however, current approaches to synchrony fail to account for the subgroup relationships, novel roles, and other behaviors that arise in large groups.

To understand how group synchronization emerges, we focus on musical synchrony, one of the most temporally precise forms of human synchronization, which arises both in skilled ensemble members and in less experienced audience members. Musical synchrony is measured in time differences, such as between musicians' production of near-simultaneous tone onsets or between audience members' claps. Thus, a deeper understanding of synchrony in musical groups offers broader implications for coordination in other group situations. Synchrony in musical ensembles is often defined **by pairwise relationships** between all group members [6–9] that capture patterns of temporal correspondence over a performance. However, pairwise relationships do not explain how context-specific interactions or **emergent properties in groups** arise between members over time that differ from individual or pairwise behaviors (see Box 1).

Box 1. Emergent properties of social groups

How do emergent properties arise in a social group? Dynamical systems theory refers to emergence in social groups as properties that result from interactions between system components that do not arise out of individual components alone [89], such as leadership that emerges in the context of a (leaderless) group of strangers. This approach focuses on factors that contribute to emergent behaviors across parts of a system [90], such as how people in one section clap together in a large audience. Social theories of teamwork focus on emergent processes that arise from the interactions among team members over time; contextual variables such as resources and rewards influence how emergent features develop in teams [91]. A musical example is the behavioral response of a musical ensemble to a member's failure to produce the correct pitch, which may depend on factors such as the performers' nervousness in the group context; the relationship between the produced error and the ongoing ensemble performance; and so forth. The interaction among these factors is not simply a combination of their separate influences but instead may represent an emergent phenomenon that would not occur if any of the factors were not simultaneously active. Emergent properties have been proposed in social psychology to explain mental and affective states [92,93]. Decisions or judgments made in a group context, for example, reflect a dynamic interplay of group members' thoughts and feelings (such as how many group members notice the pitch error in the musical ensemble) that promotes a unique Gestalt that is not reducible to the additive components of the elements [17]. Emergent properties of group synchrony overlap with several psychological theories. For example, theory of mind concepts (the tendency to attribute mental states to other people) may bear strong similarities to emergent properties of group members' synchronization [94]. Future directions for musical synchrony that can be tested in unscripted musical genres (such as improvisational jazz or dance [95,96]) include how cohesive or self-organized the group needs to be to support a theory of mind. Promising avenues include decisions at the level of musicians' actions (to play or to stop playing in the presence of an error) or decisions to change or continue the performance style produced by the group that influence the degree of musical synchrony [97].

Consider a musical octet (a group of eight musicians with no conductor, shown in Figure 1, Key figure) performing the first 2 min of Franz Schubert's 'Octet in F Major, D.803'. In the opening seconds of the octet performance (Figure 1, left), all eight instruments must sound the same musical pitch with near-perfect synchrony. Over the next 2 or 3 min in the performance (Figure 1, right), different-sized subgroups of instruments must synchronize their parts, with the most important parts (white dots) constrained by the task demands of the musical piece. The instrumentalists cannot change their physical proximity to each other during the performance; they must listen carefully to work as a team (cf. [10] for a note-by-note analysis). These continuously evolving sub- group relationships are typical of music ensemble performance in improvisational styles and jazz styles, as well as in classical music, and can occur in the absence of verbal plans [11] or an external timekeeper/conductor. Common approaches to synchrony that focus on pairwise relation- ships do not address the emerging subgroups that form in larger groups or change over time.

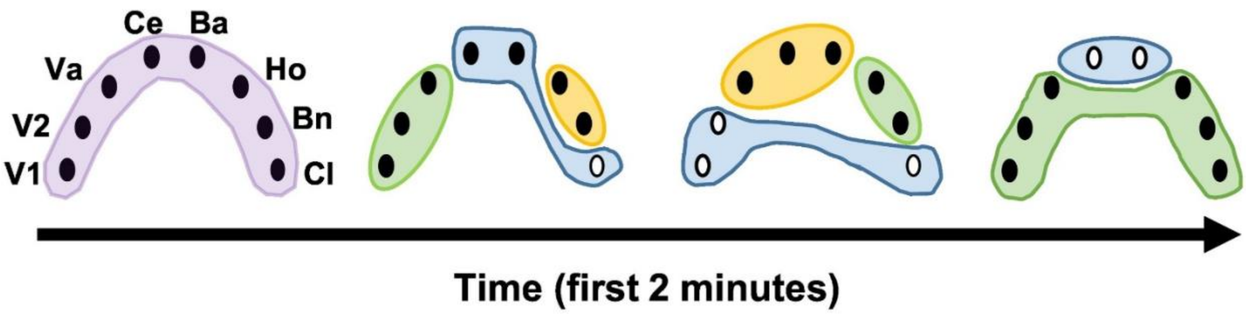

Figure 1,. Illustrative musical ensemble performance by eight players (F. Schubert's 'Octet in F Major, D.803') at four time points during the first 2 or 3 min. Each dot represents a musical instrument. Abbreviations: V1, first violin; V2, second violin; Va, viola; Ce, cello; Ba, double bass; Ho, horn; Bn, bassoon; Cl, clarinet. Colored regions indicate instrumentalists who must synchronize their parts at a specific time point in the piece. White circles represent current instrument(s) performing the most important part [10].

Drawing from the distinct paradigms of social group dynamics and **nonlinear dynamics**, we discuss fundamental properties that impact group synchrony in music: group size and group roles. First, we discuss combinatorial issues of group synchrony. Next, we present evidence from social dynamics perspectives to demonstrate that different affiliations, leadership roles, and patterns of influence occur in larger groups. We then draw from nonlinear dynamics approaches that address synchrony as an emergent group property. Finally, we tie musical group synchrony to cross-cultural comparisons and naturalistic settings such as crowd behavior at concert venues, generating new research avenues to compare healthy and disrupted patterns of behavior in larger groups [12–14].

Combinatorial approaches to group synchrony

Theoretical approaches that define musical synchrony from pairwise comparisons among all group members have an implicit assumption that each member coordinates the timing of their actions with every other member. However, the number of pairwise comparisons required for a person to compute synchrony increases unmanageably as the group size increases (Figure 2A,

thin unbroken line). The perceptual demands of increased group sizes become even more implausible when the comparisons are expanded to include subsets of all possible sizes (called N-wise comparisons; Figure 2A, thick unbroken line). Yet, subset interactions such as those shown in Figure 1
commonly arise in musical groups such as octets, in the form of cohesive subgroups [15]. A subset of four musicians in an ensemble of eight musicians, for example, can show increased synchrony during some segment of a performance based on similar rhythmic, tonal, and/or timbral relationships that arise among their parts.

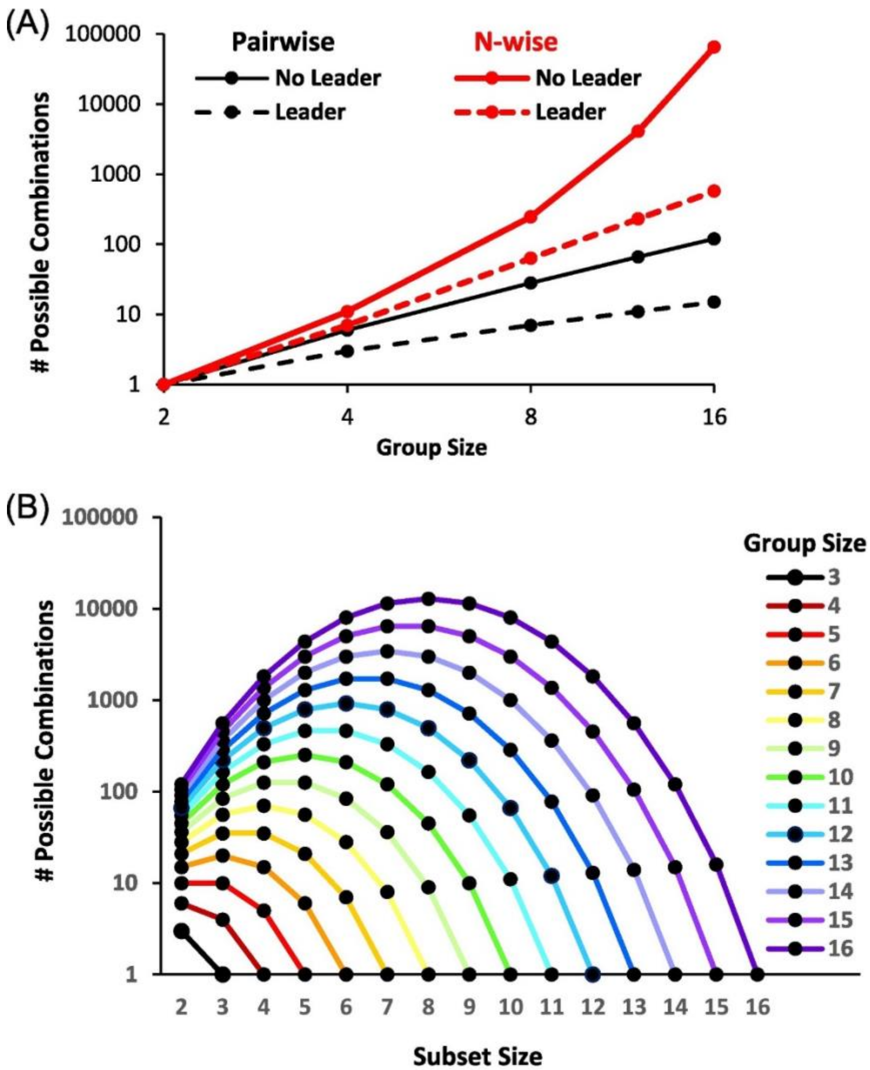

Figure 2. Combinatorial approaches to subsets in group synchrony.

(A) Number of possible pairwise and N-wise (threesomes, foursomes, etc.) comparisons by group size. Leaderless groups (unbroken line); one leader per group (broken lines). (B) Impact of group size (each line represents a different-sized group, group size = 3–16) and subset size (2–16) on the number of possible combinations.

One solution to the escalating growth of potential interactions in larger groups is to differentiate individuals on the basis of group roles. Roles such as timekeeper (e.g., the drummer in a rock band) or leader (group member currently performing the most important part) serve to direct all members' perceptions to achieve better synchrony. The presence of a leader role can reduce the required number of comparisons. Consider a musical group of eight with one leader and all pairwise comparisons that include the leader plus one other member; the set of combinational probabilities is now greatly reduced (Figure 2A, thin broken line) by the presence of a leader role, relative to the same-sized group without a leader (Figure 2A, thin unbroken line).

When N-wise subsets are considered (such as threesomes, foursomes, etc.) in which each subset contains a leader, the number of possible combinations is reduced even further (Figure 2A, thick broken line) relative to groups of the same size that do not contain a leader (Figure 2A, thick unbroken line). As group size increases, group roles further reduce the possible combinations. Although these simple comparisons do not capture the complete set of combinatorics in group membership, they do suggest two important concepts: First, increases in group size quickly rule out a pairwise combinatorial approach to synchrony, given perceptual constraints on group members; and second, group roles offer a substantial reduction in the perceptual comparisons required to achieve synchrony.

A final combinatorial issue to consider in musical group synchrony is the interaction between the group's size and the number of possible subgroups (Figure 2B). The number of possible subset interactions reaches the maximum near the midpoint (50th percentile) of the group size, which may shape a member's pressure to conform with other group members. For example, a musical group of eight has 28 possible unique subsets of size two, or 70 possible unique subsets of size four. The picture is even more complex when multiple subset sizes are considered simultaneously.
Is it easier for a group of eight to form two subgroups of size four, or two subgroups of size three plus one subgroup of size two? Future studies must evaluate if people spontaneously follow the combinatorial probabilities or apply relationship-based strategies such as the social variables of group cohesion, group roles, and norms. We consider those factors next.

Social dynamics of groups

Social dynamics researchers define a group as a set of people who are connected by the relationships between them [16], for example, by a continuous process of synchronization of gestures, looks, acts, and communication [17,18]. The success of a group's task depends on that synchronization [19–21]. Important determinants of a group's behavior include group norms (familiar routines that generate predictable interactions) [22], group cohesion (perceived connectedness) [23], group size (number of members), and group roles (intragroup relations that differentiate members' behavior and attitudes) [16,24]. Group size and group roles are important determinants that drive the members' perception of groupness (referred to as entitativity [25]) not only in social dynamics but also in musical groups whose size can be constrained (Western classical orchestra) or less constrained (Eastern gamelan).

Size matters in group synchrony

Experimentally elicited synchronous actions between individuals can increase perceptions of social bonding [26,27] while leading to more prosocial behaviors that are modulated by group size [28]. That is, different subgroup interactions can alter the relationship between group synchrony and prosociality (behaviors intended to benefit others). An explanation for the increased synchrony-prosocial behaviors with larger group size draws on neurohormonal mechanisms of endorphins, which are released during exertion and promote social bonding [29]. Musical applications propose that both passive (listening) and active (performing) behaviors result in higher endorphin levels in group members during synchronized rhythmic behaviors (clapping, tapping, dancing) [29], thus predicting increased social bonding with increased group size.

Physical proximity can interact with group size to affect synchrony. Feelings of connectedness or familiarity tend to occur between individuals who are physically proximal, whereas less connected interactions with less familiar individuals often happen over larger physical distances [30]. Physical proximity effects appear to be larger for visual cues (which can be obstructed in groups) than for auditory cues; experiments on synchronous group clapping suggest that group members respond to auditory synchrony cues independent of proximity manipulations [31]. Thus, the role of physical proximity in group size effects on synchrony may be weaker for acoustic synchrony than for (visually based) movement synchrony in social contexts where occlusions between group members can occur (e.g., in marching bands, large choirs, or orchestras).

Group roles affect synchrony

Members often take on roles within a social context that regulate the group's actions and interactions [16,24]. Group dynamics research indicates that leadership, one of the most important group roles, incorporates the critical quality of influence that leaders must enact on group members [16]. A leader's influence requires cooperation and reciprocity [32]: For leaders to impact group synchrony effectively, group members must be willing to be influenced. Although follower roles are also important in groups, fewer studies have addressed group members' willingness to be influenced by a leader during synchronization [33]. Leadership roles have been examined in musical groups, both when there is an explicit timekeeper (e.g., a conductor [34]) and when there is not (e.g., some string quartets [9]). For leaders to effectively synchronize the group, members must be responsive to the leader (such as in Figure 1). Follower roles have been tested with recordings: when musicians were told they were performing with an experimenter musician, they attributed leadership roles and performed more synchronously than when they were told they were performing with another partner [35]. Similar to the effects of social context on group roles, musicians' group roles can change across contexts: musicians can alter their synchronization to support (accompanist) or stand out (soloist) at specific points within the same performance [36]. The majority of studies examining the impact of group roles on musical synchrony have been conducted using pairwise relationships, which we discuss next.

Table 1. Common theoretical approaches to group synchrony by group size

Group size	Description	Approach[a]	Refs[a]
A. Pairwise (two-person)	Methods designed for two time series	Cross-correlations	[48,76,77]
		Cross-recurrence Quantification analysis	[78]
		Delay-coupled oscillators	[47]
		Granger causality	[79]
B. Pairwise conditionalized (multiperson)	Methods applied to two time series within a larger group while controlling for other time series	Relative phase	[55] (dyad condition)
		Transfer entropy	[80]
		Conditionalized Granger causality	[34,81,82]
		Conditioned pairwise causal entropy	[38]
		Linear phase correction	[9]
		Multivariate Granger causality	[6,8,83]
		SyncCalc	[84,85]
C. Multiperson (more than two people)	Methods designed for N time series (>2)	Joint RQA[b]	[86]
		Kuramoto-based coupled oscillators	[37,43,45,48,50,51,55]
		MdRQA/MdCRQA	[62,87]
		Multivariate surrogate synchrony	[88]

[a] Bold indicates nonlinear approach.
[b] Abbreviation: RQA, recurrence quantification analysis.

Pairwise relationships

Musical synchrony in duets has demonstrated significant effects of leadership roles, based primarily on **cross-correlations** and **Granger causality** measures. Table 1 shows common approaches to musical synchrony by group size. Table 1, Row A indicates examples of approaches used in dyadic studies. Some studies in Table 1, Row A test group roles by assigning a melody (sequence of musical notes that form a recognizable pattern) to one partner and an accompaniment (a part that supports the melody) to the other partner. Specific patterns of lag-1 cross-correlations and increased Granger causality measures have indicated the impact of leadership on synchrony, with leaders (performing the more important part) often showing more influence on followers than vice versa. The cross-correlation and **Granger causality** approaches, like other statistical **time-series** approaches, assume that the relationships among group members are time invariant; the underlying behavior is generated by a stationary process; and group relationships can be decomposed into pairwise components. Although these approaches account for asymmetric relationships such as group roles in pairwise behavior, they do not account for the entire group or subgroups as their own entities such as the left example in Figure 1. Thus, the social notion of entitativity (i.e., increasing perception of groupness with increased group size) seen in social groups and larger musical groups [37] cannot be accommodated by the pairwise approach.

Pairwise relationships have also been addressed in larger musical groups. Table 1, Row B, shows examples in which dyadic approaches are extended to larger multiperson groups by controlling for the influence of other group members on each pair. An exhaustive decomposition of the pairwise relationships among members in larger groups has shed light on group roles such as leadership. For example, Granger causality values tend to be larger between the first violin in string quartets (who often performs the melody or most important part) compared with eachother group member than vice versa [6]. Studies of movement synchrony in larger groups have modeled group-level interactions with measures of entropy; for example, conditionalized causation **entropy** evaluates entropy in each pair exhaustively while controlling for interactions with other group members [38]. Also extended from dyadic measures, conditionalized Granger causality has been applied to each pair in a larger musical group while controlling for the impact of group members outside the dyad [34]. This method, when applied to conductors' and violinists' body movements during performance, revealed that the conductor's movements Granger caused the violin section members' movements more than vice versa, thus reflecting group roles in multiperson musical synchrony.

In sum, pairwise approaches to synchrony in larger groups permit comparisons with the dyadic studies; they do not directly address higher-order interactions among more than two individuals. When the time series is not stationary across time, as is often the case, a proposed solution is to window the data by segmenting the time series into smaller (overlapping or nonoverlapping) sections. This solution's limitations are that it can yield different outcomes based on different window sizes. Windowing may also fail to detect important transition points, such as temporal instabilities seen at musical phrase boundaries or fermatas: points of prolonged duration [39]. Thus, pairwise comparisons can be powerful indicators of group roles in the context of duets but are not easily extended to multiperson groups. Next, we turn to alternative approaches from nonlinear dynamics applied to multiperson groups.

Nonlinear dynamics of group behavior

The dynamical systems approach assumes that group behavior is generated from interactions

among group members that change over time [40]. Unlike the statistical approach, the dynamical systems approach assumes the entire group is a unit or complex system whose behavior is not easily decomposable. Furthermore, each subgroup or higher-order interaction is assumed to yield different outcomes across group contexts. For example, it is common for musicians in real-world scenarios to perform in synchrony with unfamiliar performances (e.g., stage musicians
who are reassigned to different ensembles). Nonlinear dynamical systems demonstrate, in addition, emergence in interactions among elements that cannot be reduced to a linear combination
of properties of those elements [40]. According to the nonlinear dynamics view, the statistical approaches exemplified by Granger causality and cross-correlation analyses can describe outcomes but cannot explain why the interactions among group members change across contexts. We highlight the advantages and disadvantages of nonlinear dynamics applied to musical synchronization in larger groups in the following paragraphs.

Multiperson approaches to synchrony such as those in Table 1, Row C, use strikingly different assumptions to understand the behavior of groups larger than dyads and their fluctuations over time. One important assumption of Table 1, Row C is that the individual compares themselves with the group rather than with each other group member (Table 1, Rows A and B), which allows
the reduction in perceptual demands for the individual situated in larger groups. All of the Table 1,
Row C approaches rely on nonlinear dynamics. Many of the Table 1, Row C approaches rely on variants of the Kuramoto oscillator model [41,42]: a mathematical description of oscillators whose coupling with other oscillators is based on nonlinear differential equations. The Kuramoto model has been used to simulate effects of different interactions among oscillators as a function of coupling strength. Inspired by this approach, Frank, Chauvigné, Richardson, and colleagues [43–45] have implemented a cluster phase approach in synchrony measures of group members' dance and rocking chair motions. This measure compares each group member with the group mean phase over time, thus treating the group as an entity.

One study of group drumming contrasted pairwise comparisons with group mean phase measures by manipulating group size (two, four, and eight members) within the same set of individuals [37]. Only the groups of size two showed the expected lag-1 cross-correlations indicating temporal adaptation from one tone interval to the next, similar to the duet synchrony patterns described in Table 1, Row A. Larger groups of four and eight showed decreased cross-correlations, indicating that the larger subgroups displayed different behaviors from the pairs of which they were composed. In addition, mean-field values representing the global coupling among all oscillators or group members [46] indicated that temporal variability decreased as the group size increased, again suggesting the entire group was an entity [37]. These patterns of interaction group interactions beyond the dyadic comparisons, captured by approaches in Table 1, Row C, are not captured by the pairwise extensions in Table 1, Row B.

Kuramoto-inspired approaches to musical group synchrony have been applied in several extensions. One captures leadership roles in duet performance [47,48]. Another addresses perceptual proximity influences on the group mean [49], related to the previously described social effects of proximity on synchrony in group contexts. Finally, recent extensions of the Kuramoto model to group behavior in nonmusic tasks have introduced weighting terms for different group members that may account for how group roles emerge in larger group sizes [50,51]. Another nonlinear modeling approach, called the Haken-Kelso-Bunz model [52], which captures bistability in bimanual coordination, has been extended to model group synchrony [53,54]. This model could be applied to in-phase and anti-phase actions of performers in a musical group, such as performers who take turns producing their parts.

Concluding remarks and future directions

Social group dynamics and nonlinear dynamics provide several insights for understanding musical synchrony in larger groups without relying solely on pairwise comparisons, allowing scientists to think about synchrony in a way that might better (i) match findings of social group dynamics and (ii) reduce the perceptual demands on group members. We propose that future modeling efforts of musical group synchrony apply a computational approach that emphasizes group roles and group size. This approach should include asymmetric coupling between group members in large-group synchronization, individuals' ability to alter that coupling during the time course of performance [55,56], and leadership that arises spontaneously in synchronization tasks [38]. Social dynamics suggest that perceptual and social pressure to conform with other group members is affected by factors of group size and group roles. For example, musical group instability, which can result in reduced synchrony, may peak at the midpoint of the subset size (Figure 2B) and thus yield increased pressure toward smaller subsets (left of Figure 2B) or larger subsets (i.e., smaller numbers of group members per subset; right of Figure 2B) as group size increases. This prediction is consistent with how the number of unique melodic voices in large musical groups tends to be small, thus requiring group members to make fewer comparisons with other subgroups who are performing different musical parts. Performance errors may shed light on whether breakdowns arise at the individual, pair, or subset levels of groups [57,58].

A novel theoretical framework for musical group synchrony is sorely needed at a time when crosscultural comparisons and naturalistic settings such as crowd behaviors have become a new focus. Music scientists have a growing interest in sociocultural and cognitive behaviors beyond those of stylized Western music performance [59], and some researchers argue that social bonding is the primary connection among musical behaviors across cultures and geographies [60]. Comparison of culture-specific and culture-general aspects of music within nine geographically diverse global regions identified strong statistical commonalities that included not only basic features of pitch and rhythm but also, most important for our purposes, performance style and social context; for example, music tends to be performed in groups [61].

Three avenues are especially important now for future directions in musical group synchrony. First, further development of nonlinear multidimensional approaches such as recurrence quantification analysis [62,63] holds promise for comparing underlying factors that affect group members at critical time points. For example, the weighting of asymmetric relationships in larger subgroups such as trios is essential for understanding interactions of group size with emerging group roles (consider a violin-cello-piano trio in which the leader changes over time; the violin may affect the interaction of piano and cello differently from how the piano and cello interaction affects the violin – both of which can change over time). These complex interactions are normal behavior in a musical ensemble.

Second, hierarchical models that capture relationships among subgroups should be developed for larger musical groups such as bands and orchestras. Recent extensions of hierarchical autoregressive models [64] and coupled nonlinear oscillators [55,65] have assumed hierarchical nesting within levels, with no overlap between subgroups within a level, a claim that does not permit group members to hold more than one role or to move between subgroups (as suggested by emergent norms theory and Figure 1).

Third, group synchronization should be examined in human–machine interactions, research that is already advancing in pairwise comparisons [66–70]. The inclusion of one or more virtual partners in synchrony with one or more humans will permit specific interactions between subgroups to be tested [71]. This paradigm calls for asymmetric agent-to-agent coupling to test the development of group roles over time, such as how popular music ensembles lay down tracks with prerecorded partners in recording studios, or how individual musicians practice in music-minus-one recordings when the musical ensemble is not available.

In sum, social dynamics and group dynamics offer insights into group synchrony in a wider range of behaviors, such as chants or cheers at a soccer match, dancing together at a concert, or marching in a parade. Dynamical theories explain the behaviors of larger groups as selforganizing and arising from nonverbal cues to movement, similar to how musicians signal upcoming events with body movements [6,72]. Social theories also address behaviors of larger groups: A leader or salient individual often supplies the group's goals in the absence of social norms [73]. Behavioral norms such as leadership emerge over time as new social norms for the group are formed [74]. Given the social pressures for people to stay 'in sync', it is also important to ask when synchrony ceases. Social dynamics and group dynamics offer promise for understanding how and when groups synchronize; whether changes in group size (through attrition or growth) influence the emergence of new roles; and how leaders are identified by movement, personality, or an ability to synchronize the group [75] (see Outstanding questions).

Glossary

Cross-correlations: linear measures of similarity between two time series as a function of temporal displacement of one time series relative to the other.

Emergent properties in groups: a feature or behavior that arises from interactions among group members that cannot be explained by the parts of a group (such as individuals or pairs) considered alone or outside the context of the group.

Entropy: concept or measure of a system's disorder, randomness, or uncertainty, used in information theory to define information loss. Some entropy measures have been extended to pairwise approaches (Table 1).

Granger causality: a statistical test of temporal relationships between two time series, measured by whether one time series predicts or forecasts the other time series. Granger causality analyses have been extended to conditional pairwise approaches (Table 1).

Kuramoto oscillator model: a set of coupled oscillators that synchronize without the need for a central controller or coordinator, such as an internal clock. Oscillators have a natural frequency (which determines their rate) and can adapt to other oscillations that share a natural frequency. When oscillators couple with each other (exchange information that aligns their outputs in time), they exhibit changes in relative phase and/or period in their response.

Nonlinear dynamics: study of systems that change over time, with an emphasis on nonlinear (nonadditive)

Outstanding questions

How do group size and group roles reduce the perceptual comparisons required to achieve musical synchrony?

How does pressure to conform with others change as group size increases?

How do group members in large musical ensembles maintain different roles (e.g., section leader or follower) and change those roles throughout a performance?

How do diverse musical performance genres (improvisational jazz, classical Western tonal music, human-machine electronic music) change the effects of group roles on synchrony?

Does the positive relationship sometimes observed between increased musical synchrony and interpersonal affiliation in dyads extend to groups of different sizes and roles?

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