Author(s): Hartmann, Martin; Carlson, Emily; Mavrolampados, Anastasios; Burger, Birgitta; Toiviainen, Petri

Title: Postural and Gestural Synchronization, Sequential Imitation, and Mirroring Predict Perceived Coupling of Dancing Dyads

Year: 2023

Version: Published version

Please cite the original version:

Hartmann, M., Carlson, E., Mavrolampados, A., Burger, B., & Toiviainen, P. (2023). Postural and Gestural Synchronization, Sequential Imitation, and Mirroring Predict Perceived Coupling of Dancing Dyads. Cognitive Science, 47(4), Article e13281. https://doi.org/10.1111/cogs.13281

COGNITIVE SCIENCE
A Multidisciplinary Journal

Cognitive Science 47 (2023) e13281

ISSN: 1551-6709 online
DOI: 10.1111/cogs.13281

Postural and Gestural Synchronization, Sequential Imitation, and Mirroring Predict Perceived Coupling of Dancing Dyads

Martin Hartmann,[a,b] Emily Carlson,[a,b] Anastasios Mavrolampados,[a,b]
Birgitta Burger,[c] Petri Toiviainen[a,b]

[a] *Centre of Excellence in Music, Mind, Body and Brain, University of Jyväskylä*
[b] *Department of Music, Art and Culture Studies, University of Jyväskylä*
[c] *Institute for Systematic Musicology, University of Hamburg*

Received 6 April 2022; received in revised form 1 March 2023; accepted 23 March 2023

Abstract

Body movement is a primary nonverbal communication channel in humans. Coordinated social behaviors, such as dancing together, encourage multifarious rhythmic and interpersonally coupled movements from which observers can extract socially and contextually relevant information. The investigation of relations between visual social perception and kinematic motor coupling is important for social cognition. Perceived coupling of dyads spontaneously dancing to pop music has been shown to be highly driven by the degree of frontal orientation between dancers. The perceptual salience of other aspects, including postural congruence, movement frequencies, time-delayed relations, and horizontal mirroring remains, however, uncertain. In a motion capture study, 90 participant dyads moved freely to 16 musical excerpts from eight musical genres, while their movements were recorded using optical motion capture. A total from 128 recordings from 8 dyads maximally facing each other were selected to generate silent 8-s animations. Three kinematic features describing simultaneous and sequential full body coupling were extracted from the dyads. In an online experiment, the animations were presented to 432 observers, who were asked to rate perceived similarity and interaction between dancers. We found dyadic kinematic coupling estimates to be higher than those obtained from surrogate estimates, providing evidence for a social dimension of entrainment in dance. Further, we observed links between perceived similarity and coupling of both slower simultaneous horizontal gestures and posture bounding volumes. Perceived interaction, on the other hand, was more related to coupling of faster

---

Correspondence should be sent to Martin Hartmann, Centre of Excellence in Music, Mind, Body and Brain, University of Jyväskylä, P.O. Box 35, Jyväskylä FI-40014, Finland. E-mail: martin.hartmann@jyu.fi

simultaneous gestures and to sequential coupling. Also, dyads who were perceived as more coupled tended to mirror their pair's movements.

Keywords: Full-body coupling; Entrainment; Convex envelope; Time-frequency analysis; Time-delay analysis; Mirroring

1. Introduction

Body movement has been regarded as a paramount nonverbal means of human communication. Indeed, it has been shown that body movements can help observers extract robust information about actions, intentions, emotions, or traits such as sex or personality (Dahl & Friberg, 2007; Frith & Frith, 2007; Knoblich & Sebanz, 2006). This kind of information can be conveyed through human movements even when these are reduced to relative motions of few high-contrast light points attached to moving bodies (see Johansson, 1973). When observing coordinated social behaviors, such as walking or dancing together, there is information available about both individual motor control and mutual adjustment between the actions of two or more individuals: jointly performed movements carry rhythmic and social aspects of coordination, two facets that are inherently intertwined in the perception of social coupling (Dumas, Laroche, & Lehmann, 2014). The question remains as to what specific aspects of jointly performed movements can communicate the extent of interpersonal coupling to observers. Given that dance encourages a wide variety of individual rhythmic and coordinated social movements, the study of joint dance and its perception can provide rich insights into social cognition.

Dance is a human behavior known in all cultures, often appearing in social contexts and in conjunction with music. As an energetically expensive activity, this prevalence suggests that dance may have provided fitness benefits to early humans (Christensen, Cela-Conde, & Gomila, 2017). Various accounts have posited a number of evolutionary roles for human dance, including its ability to communicate credible social information (Fink, Bläsing, Ravignani, & Shackelford, 2021), facilitate group functioning during times of social transition (Cross, 2001), stimulate neurohormonal pathways associated with social cohesion (Tarr, Launay, & Dunbar, 2016; Wiltermuth & Heath, 2009), and support cognitive and brain plasticity (Muiños & Ballesteros, 2021). Laland, Wilkins, and Clayton (2016) have suggested that dance may have evolved as an exaptation of imitative motoric behavior, which has been shown to have bidirectional benefits within cooperative social interactions, as in the so-called chameleon effect (e.g., Chartrand & Bargh, 1999; Lakin, Jefferis, Cheng, & Chartrand, 2003). Ravignani and Cook (2016), however, have argued that the precisely timed motoric interactions that characterize dance and other social behaviors could reflect a species-general timing mechanism for social interactions arising from competition rather than cooperation.

Regardless of the ultimate evolutionary cause, a key aspect of dance, as it occurs in social settings, is the complex motor coupling[1] that arises between dancers moving together in time to the same music. A large body of research has described humans' ability and tendency to synchronize bodily movements, such as the tapping of a finger, to auditory signals (Repp, 2005; Repp & Su, 2013). In the presence of periodic auditory (isochronous) stimuli presented with interonset intervals between approximately 100 and 2,000 ms, humans are not only capable of highly precise motoric entrainment but often do so even without conscious intention. Motoric entrainment is therefore afforded by music with a periodic pulse or beat, particularly music with tempi of around 2 Hz (120 BPM), which corresponds to the average spontaneous tempo of locomotion in humans (MacDougall & Moore, 2005; Merker, 2014). Visual-motor coupling has also been observed with stimuli such as a pulsing light or the rhythmic movements of another person (Grahn, 2012). The latter condition has been described by Phillips-Silver and Keller (2012) as social entrainment. Trained dancers have been shown to be more effective at visual-motor coupling in tasks that involved motor coordination with another actor (Washburn et al., 2014), suggesting a relationship between the interpersonal motor coupling that occurs in dance and in everyday life. For the purpose of this study, coupling could be defined as a manifestation, or outcome, of rhythmic entrainment (a stimulus-driven, auditory process of synchronization to an acoustic signal) and social entrainment (a mostly interpersonal and visual process of coordination).

Dance represents an especially complex example of naturally occurring rhythmic-social entrainment, which has not yet been studied to the same extent as more simplified examples, such as finger tapping. Research on individual dance movement has demonstrated that entrainment occurs simultaneously at different time scales as per multiple musical beat levels; that is, a dancer may bounce vertically in time with each beat and simultaneously sway mediolaterally every four beats (Toiviainen & Carlson, 2022; Toiviainen, Luck, & Thompson, 2010). In a social context, visual and auditory modalities may be tightly intertwined; that is, there is likely to be both individual entrainment to the music as well as entrainment between the dancers based on mutual exchange of visual information. A useful paradigm for understanding these related influences on behavior comes from Kenny's (1996) model of nonindependence, which distinguishes partner effects, mutual influence, and common fate. In the case of dance, the former two constitute one- and two-way exchange of visual information between partners, while auditory information from the music represents a common fate that may result in behavioral similarity regardless of social influence. When dance movements are spontaneous rather than pre-determined by choreography (i.e., the type of dance which often occurs in contexts such as clubs or parties), this situation is further complicated as entrainment occurring between dancers based on visual information may not result in identical movements. Recent findings on the influence of visual and auditory coupling upon synchrony in choreographed dance have led to the interpretation that vertical movements are more prone to synchronize to discrete auditory events such as musical beats, whereas movements in the horizontal plane are more likely to match visual stimuli (Chauvigné, Walton, Richardson, & Brown, 2019). However, it is neither known whether similar insights could be derived from free dance movement contexts, nor whether these possible relations influence the visual perception of dance. Understanding this point would help to pinpoint what specific body movements influence the perception of social interactions and, more specifically, to better grasp the possible impact of direction and speed of coupling on the perception of rhythmic and social entrainment in dance.

The role of visual information in dance suggests perceptual research on synchrony as a useful means of exploration. When rating observed coordination or rapport, observers seem to pay attention to various kinds of information, including social factors such as skin tone similarity (Lumsden, Miles, Richardson, Smith, & Macrae, 2012; Macpherson, Fay, & Miles, 2020). Noteworthy, work on visual and auditory perception of simulated dyads walking side by side (Miles, Nind, & Macrae, 2009) has shown that also the manner in which behavior is coordinated, that is, whether interpersonal coordination modes are stable (i.e., in- or antiphase) or not, seems to have an impact upon perceived interpersonal rapport. Such a correspondence between observed quality of social exchanges and the bistability condition predicted for slower coordinated movement by the Haken–Kelso–Bunz (HKB) model (Haken, Kelso, & Bunz, 1985) is a clear example of the perceptual impact of higher-order structures of interpersonal engagement called *interpersonal synergies* (see, e.g., Riley, Richardson, Shockley, & Ramenzoni, 2011).

Back to dance research, relatively few systematic studies have been conducted on dance perception. While this research has, until recently, been mostly limited to individual dancing (Chang et al., 2016), two research pathways to study relations between perceived and kinematic motor coupling between dancers can be identified. The first one entails experimental manipulation, such as the use of choreography to create alignment or misalignment. Lee, Launay, and Stewart (2020), for example, have shown that perception of social closeness and powerfulness is higher for temporally aligned performances than for experimentally misaligned performances. This corroborates previous findings that, when choreography or silent disco has been used to facilitate or inhibit entrainment between dancers, participants who were entrained subsequently report greater social closeness (Tarr et al., 2016) and perform better on social memory tasks (Woolhouse, Tidhar, & Cross, 2016) and vice versa. Disadvantages regarding ecological validity have led to a second research pathway focusing on the perceptual validation of kinematic coupling features from naturalistic movement. Main findings derived from this research paradigm suggest that mutual gaze plays a role on perceived coupling in dyadic dance: the extent to which dancers are horizontally oriented toward each other is an important predictor of perceived coupling (Carlson, Burger, & Toiviainen, 2019; Hartmann et al., 2019). However, the kinematic correlates of perceived coupling in dyads that are highly oriented toward each other remains an important empirical question. While it seems clear that proxemic behaviors such as interpersonal orienting can overperform interpersonal synchrony in the prediction of subjective evaluations of social interactions (Lahnakoski, Forbes, McCall, & Schilbach, 2020), the specific contribution of synchrony to subjective kinematic evaluations still requires investigation. Tackling this issue would allow to go beyond the current understanding of dance coupling by elucidating percepts beside mutual gaze that observers would pay attention to when rating perceived dance coupling.

While the terminology used may vary somewhat among researchers and across disciplines, studies on kinematic coupling quantification often make a distinction between interpersonal *synchrony* and behavorial *imitation* (Crone et al., 2021; Hu, Cheng, Pan, & Hu, 2022; Lakin, 2013). The difference between these two notions—whether the coupling is time delayed or not—might be quite relevant from a perceptual viewpoint: unison choreographies can be very dissimilar to leader–follower relations or turn-taking patterns. Further insights have been gained through the study of these forms of coupling and their possible links with perceptual coupling dimensions—such as similarity and interaction between dancers. It has been shown, for dyads dancing to pop music, that perceived similarity was mainly predicted by features describing spatiotemporal coupling (i.e., synchrony) whereas perceived interaction related more to the extent to which the dancers were facing toward each other while coupling, which could be deemed as favoring imitation (Hartmann et al., 2019). It is thus plausible to expect relationships between similarity and simultaneity on one hand, and between interaction and sequentiality on the other hand. However, this issue has not yet been addressed in the literature. A better understanding of possible similarity–simultaneity and interaction–sequentiality interconnections might help to develop insights on the relationship between passive similarity and active communication, which have been regarded as two interrelated "faces of the coin of coupling" (Dumas & Fairhurst, 2021) and, specifically, to unravel differences between—and develop predictor measures of—judgments of similarity and interaction in joint dance.

Besides the dichotomy between sequentiality and simultaneity, it is possible to distinguish modes of coupling that are clearly associated with gestures (directional movements) to those that involve body posture (Feniger-Schaal & Lotan, 2017). Among the relatively few postural features that can be found in dance movement research, we shall highlight those related to Laban and Ullmann's (1966, p. 10) notion of personal space or *kinesphere* ("the sphere around the body whose periphery can be reached by easily extended limbs without stepping away from that place which is the point of support when standing on one foot"), onto which polyhedra are overlaid to construct a net of orientation points. Elliptic, rectangular, and polyhedral geometric descriptors have not only been used in studies on dance performance evaluation (Hachimura, Takashina, & Yoshimura, 2005) and emotion perception (Camurri, Lagerlöf, & Volpe, 2003), but also in human action recognition (Ramezanpanah, Mallem, & Davesne, 2020) and expressive motion recognition (Ajili, Ramezanpanah, Mallem, & Didier, 2019) literature (named "Contraction Index" in Camurri et al., 2003, and "Shape Flow" in the other articles). To the best of our knowledge, this feature has not been investigated in the context of interpersonal coupling. Studying the simultaneous matching between dancers' bounding volumes might shed light on whether people pay attention to posture similarity when rating perceived coupling in dance. This is a corollary question to that of the types of coordination that are used as a means of communication, which can have implications to evolutionary accounts of music and dance (see, e.g., the coalition strength signaling theory proposed by Mehr, Krasnow, Bryant, & Hagen, 2021).

Another relevant issue is the role played by hand movements in the coupling process. In line with research showing the importance of hand gestures in spoken communication (Bernardis & Gentilucci, 2006; Krauss, Chen, & Chawla, 1996; Skipper, Goldin-Meadow, Nusbaum, & Small, 2007), Carlson et al. (2019) found that dancing dyads who move their hands faster tend to be perceived as more interactive, and vice versa. Unresolved issues regarding hand movements in dance include whether they make a unique contribution to full body coupling and whether they outperform it. Answering these questions might allow for increased insights into the relative importance of local and complex gestures as opposed to more global and simpler gestures (such as bouncing) upon dance movement coordination and its perception.

It is also possible that partner-facing dancers tend to mirror each other's movements. For instance, one dancer might extend her left arm to her left as the other dancer would extend her right arm to her right, producing a mirror-reversed copy of the observed movement. Recent research on social interaction has found behavior matching (posture mirroring) to be a predictor of empathic accuracy (Fujiwara & Daibo, 2022). Previous dyadic dance studies, however, disregarded the phenomenon of horizontal mirroring between dancers. On a more general note, to the best of our knowledge, the effects of horizontal mirroring upon estimates of "pairwise coupling" (i.e., coupling between corresponding body parts and movement directions) are yet to be investigated. Clarifying these issues can help to understand the influence of mirroring upon estimated coupling, give hints on its contribution to perceived coupling, and more generally provide new insights on the relative impact of interpersonal mirroring upon joint action observation.

A question that arises in social interaction research is the extent to which the quantified synchrony involves an exchange of information between agents. Psychological studies on nonverbal dyadic synchrony have compared videos with actual dyads and artificially coupled dyads (Bernieri, Reznick, & Rosenthal, 1988) and, more recently, applied surrogate data generation methods to differentiate synchrony from pseudosynchrony (i.e., spurious) estimates (Moulder, Boker, Ramseyer, & Tschacher, 2018). However, to the best of our knowledge, dyadic dance studies have not explored the possible effects of an artificial matching of dyads upon coupling estimates. It would be important to clarify whether synchronous coupling outperforms pseudosynchronous coupling in this context to help unravel the relative contribution of social entrainment upon dyadic dance coupling. This can also help to grasp the interplay between individual rhythmic and coordinated social movements and their effects upon subjective judgments of interpersonal coupling.

There is also a need to develop richer computational methods to quantify coupling (Dumas & Fairhurst, 2021). Specifically, movement coupling dynamics can be characterized in various application domains by two types of temporal phenomena. First, assuming that visual-motor coupling between dancers occurs simultaneously at same and different temporal scales, multiscale analytical approaches are necessary to capture the full extent of social entrainment in this context. Second, coupling involves not only synchronous but also time-delayed responses (Konzack et al., 2017); that is, a distinction between concurrent (or synchronous) and sequential entrainment is necessary (Wass, Whitehorn, Marriott Haresign, Phillips, & Leong, 2020). Both phenomena have been largely understudied in the social dance context. Finally, multivariate approaches are fundamental for this endeavor, because different body parts and movement directions can exhibit variation in extent and modes of coupling.

The current study arose from the basic premise that observers will be able to distinguish highly from weakly coupled dancers even when all dancers are oriented toward each other. A second premise was that synchronous and imitative dance coupling are multidimensional phenomena: coupling occurs simultaneously at multiple movement instantaneous frequencies (multiple musical beat levels) and sequentially at multiple time intervals. The aim of the current study is therefore to unravel the contribution of coupling frequency and sequentiality to the prediction of perceived coupling between dyads highly oriented toward each other. The following research questions were addressed in the current study:

- RQ1: What coupling modes (i.e., synchronous, imitative) are associated with judgments of coupling between partner-facing dancers?
- RQ2: What is the contribution of different movement directions, body parts, and mirrored movements to the perception of coupling between partner-facing dancers?

Based mainly on previous studies, we proposed the following hypotheses regarding dyadic coupling in itself and in relation with its perception:

- H1: Perceived coupling mainly relates to vertical coupling at a 1-beat level and to horizontal coupling at a wider range of beat levels and lags, following the "auditory-vertical, horizontal-visual" association (see Chauvigné et al., 2019).
- H2: Perceived similarity is more associated with simultaneous coupling, whereas perceived interaction and leader-followership better relate to sequential coupling (see generally Hartmann et al., 2019).
- H3: Compared to other body parts, hand movements make a relevant contribution to the prediction of perceived coupling from full body kinematic estimates (see Carlson et al., 2019).
- H4: Coupling estimates yield increased prediction accuracy after horizontally mirroring the movement data by switching opposite body parts to match body sides.
- H5: Real dyads exhibit more kinematic coupling than artificially matched dyads.

To address these issues, we carried out an online study in which participants were asked to watch silent stick figure animations of dancing dyads and rate the degree of coupling between them. The animations were derived from data collected as part of a naturalistic motion capture study in which participants danced in dyads to different musical styles. Three kinematic features were extracted from the movement data to quantify the degree of kinematic coupling between each dyad and subsequently correlated with the perceptual responses.

This study is a follow-up to Hartmann et al. (2019), which focused on the kinematic prediction of perceived dyadic dance coupling using latent space variables. Comparing both publications, Hartmann et al. (2019) presented dyadic animations with a large variance in frontal orientation between dyad members, whereas this study focuses only on front-facing dyads to explore what aspects beside mutual gaze are paid attention to when judging perceived dyadic dance coupling. Further, the current study reports results based on a larger number of dyadic animations presented to observers (128 vs. 59), larger number of observers (432 vs. 83).

2. Materials and methods

The motion capture study described below took place at the Department of Music, Art and Culture studies of the University of Jyväskylä. An online perceptual experiment was designed at the Department of Music, Art and Culture studies and the Faculty of Information Technology of the University of Jyväskylä and published as a set of questionnaires in SurveyMonkey (Momentive, San Mateo, California; https://www.surveymonkey.com/).

2.1. Ethical approval and informed consent

All experiments were performed in strict accordance to guidelines and regulations of the National Advisory Board on Research Ethics in Finlasnd (TENK, see https://www.tenk.fi/sites/tenk.fi/files/ethicalprinciples.pdf) relating to research in the humanities and social and behavioral sciences, which the University of Jyväskylä Ethical Committee adheres to. According to these guidelines and regulations, ethical permission was not required for this research.

Participation in the motion capture study and the online perceptual experiments was completely voluntary and was organized and supervised by study authors. The key experimental procedures were explained to participants in advance. Participants gave their written consent for participation in the experiments and for further use of the collected research data in this research project and on potential follow-ups. Participants were informed that they could withdraw from the research at any time. While the general purpose of the motion capture study and the perceptual experiments was communicated to them, they were not informed at any point about the research hypotheses. Finally, participants were debriefed as to study objectives.

2.2. Motion capture study

Free dance movement data were collected from participants in a dyadic setting using naturalistic (i.e., commercially available) musical stimuli (see Hartmann et al., 2019 for a more thorough description of this study).

2.2.1. Participants

Participant recruitment for the motion capture experiment was done through social media and university e-mail lists. Seventy-three (52 female) participants, aged 19–40 years (M = 25.75, SD = 4.72), completed the experiment. Participants were of 24 different nationalities and received two movie ticket vouchers as a token for their participation.

2.2.2. Apparatus

A 12-camera optical motion capture system (Qualisys Oqus 5+) was utilized to record participants' movements. Three-dimensional tracking of 21 reflective body markers attached to each dyad member was performed at a frame rate of 120 Hz. Marker locations are shown in Fig. 1A. Musical stimuli were randomly presented to participants using four Genelec 8030 A loudspeakers and a subwoofer. Synchronization between the motion capture data and the musical stimuli—which was required for further data trimming—was possible by jointly recording, using ProTools software, the direct (line-in) audio signal of the playback with the synchronization pulse transmitted by the Qualisys cameras during data capture.

2.2.3. Procedure

Participants were instructed to move freely in dyads to the musical stimuli, as they might in a dance club or party setting. The stimuli, ranging from 97 to 132 BPM, comprised 16 excerpts from 8 musical genres: Blues, Country, Dance, Jazz, Metal, Pop, Rap, and Reggae (two stimuli per genre). These stimuli, chosen automatically based on social tagging data, are

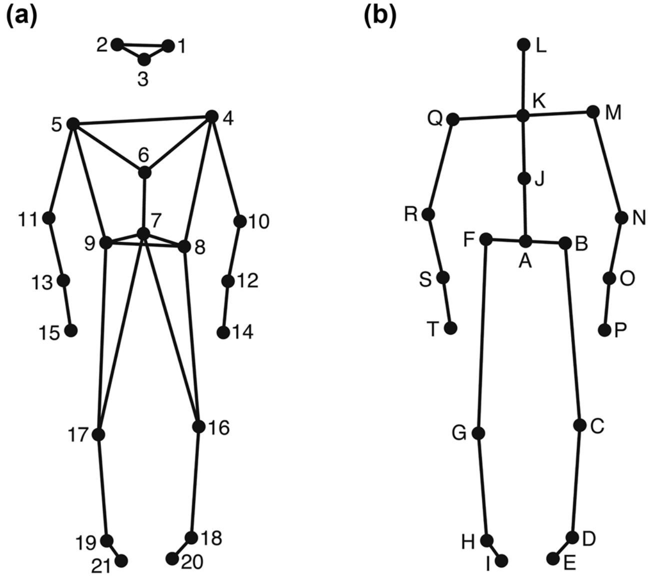


Fig. 1. Stick figure illustrations of marker and joint locations. (A) Anterior view of the original marker locations. (B) Anterior view of the locations of the reduced secondary markers/joints used in animation and analysis of the data.

highly representative of the chosen genres (as fully described in Carlson, Saari, Burger, & Toiviainen, 2017).

2.2.4. Stimuli processing and animation

A total of 1440 movement recordings from 90 dyads were processed in MATLAB R2021a (Natick, Massachusetts) using the Motion Capture (MoCap) Toolbox (Burger & Toiviainen, 2013). After trimming to match the exact duration of the musical excerpts, gaps in the data were linearly filled and resampled to 60 Hz. Data were then trimmed a second time to the length of the shortest recording (24.5 s), and finally, the last 8 s of each excerpt were selected for further preprocessing (i.e., from 16.5 until 24.5 s). This duration, which was chosen to avoid experimental fatigue, had been previously tested in a pilot experiment. Following this, the data were transformed into a set of 40 secondary markers, subsequently referred to as joints, of which there were 20 per dyad member (see Carlson et al., 2019 for a more thorough description of this transformation). The locations of these 20 joints are depicted in Fig. 1B.

Subsequently, we measured the extent to which the dyad members were front facing each other using a feature called *Orientation* (Carlson et al., 2019; Hartmann et al., 2019; see Bamford, Burger, & Toiviainen, 2023 for a similar measure). The purpose of this procedure was to select, for the perceptual experiment, a set of 8 dyads having maximal mean torso orientation across the 16 musical stimuli. The mean orientation of the selected dyads across the 16 recordings varied between .93 and .97, while the value of this feature ranges between −1 (perfectly oriented in opposite directions) and 1 (perfectly oriented towards each other).

Next, silent animations of the movement data were generated at a rate of 30 frames per second and rendered in color such that one dyad member was animated in green and the other in red. Animations were created without audio so that observers would focus on coupling between dancers rather than on synchronization to the music. Before generating the animations, the movement data were processed to maximize the similarity between different animations by making the stick figures of each recording appear to have the same average size in the image plane and ensuring that they did not overlap with each other. First, the position of the dyad in the horizontal dimensions was mean centered based on the mean horizontal coordinates of the root markers. Next, the data were rotated so as to set the slope between these coordinates to zero. To avoid the possibility that the position of the dancer on the left or right would affect participants' perceptions, spatial reversal was applied to a randomly selected half of the animations.

2.3. Perceptual experiment

The motion capture data animations were presented to participants in an online experiment on visual perceptions of interpersonal coupling in music-induced movement (Fig. 2). This experimental procedure has been adapted from previous studies on dyadic coupling in dance (Carlson et al., 2019; Hartmann et al., 2019).

2.3.1. Stimulus selection

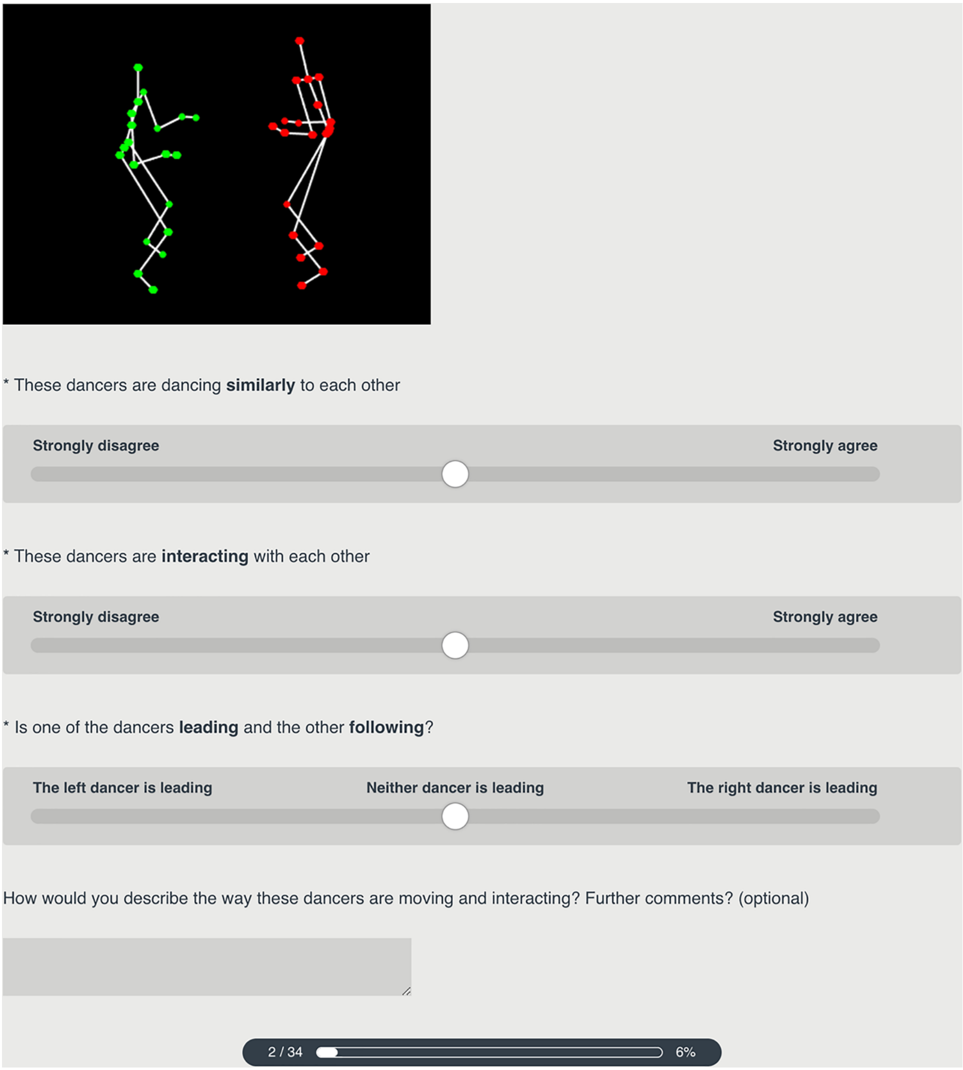
The selected partner-facing dyads (two male–female dyads, six female–female dyads) were based on 11 dancers (10 females), five of whom danced in two of the selected dyads. Dancers were of nine different nationalities (two Finnish, two French, one Chinese, one Ethiopian, one Iranian, one Lithuanian, one Scottish, one Turkish, and one Vietnamese) and their mean age was 26 years ($SD = 2.53$).

The movement data (16 musical stimuli × 8 dyads) were allocated without replacement into four partitions following a Latin rectangle combinatorial design. The purpose of this partitioning was to keep the duration of the experiment sufficiently short (∼26 min) to minimize fatigue. Fig. 3 shows this design, where the partitions are distinguished using different colors. Within each partition ($N = 32$), each dyad appeared four times and each musical stimulus was danced to twice.

After giving their consent for participation, participants joining the online experiment were randomly redirected to one of four versions of the same experiment, each of which corresponded to a different partition of the animation dataset. From the dataset of 128 animations, a unique subset of 32 was utilized for each version of the experiment.

2.3.2. Participants

Participant recruitment for the online study on dance movement was done through social media and e-mail lists. From a total of 518 questionnaire responses across all four partitions, 432 responses (269 females; 108 participants per partition) were kept for further analysis after excluding outliers and matching raters from different partitions based on gender and age (see below). Selected participants were of 60 different nationalities, primarily from United



* These dancers are dancing **similarly** to each other

* These dancers are **interacting** with each other

* Is one of the dancers **leading** and the other **following**?

How would you describe the way these dancers are moving and interacting? Further comments? (optional)

Fig. 2. Perceptual study self-guided interface.

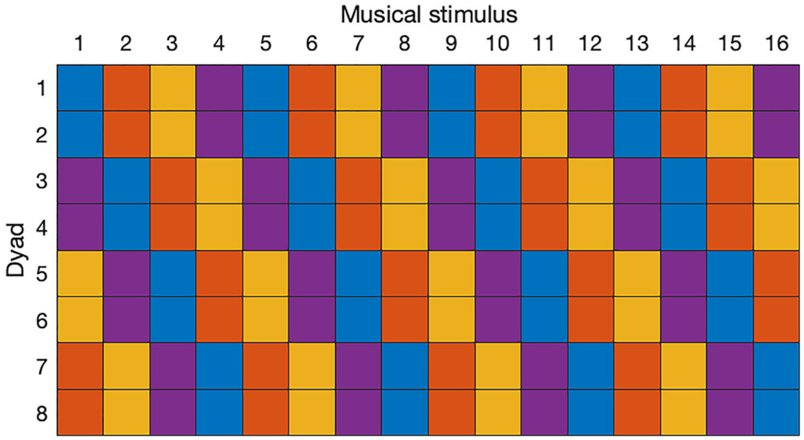
States (163), United Kingdom (37), Germany (21), Finland (19), Belgium (15), France (10), and Italy (10), and their mean age was 34.64 years (SD = 10.84); see Table 1 in Results for summary statistics per partition and across partitions over several variables. In exchange for their participation, raters had the option to enter a prize draw for one of 40 €25/$30 vouchers from a worldwide retailer.

2.3.3. Procedure

The main part of the online survey, which largely follows previous work (Carlson et al., 2019), consisted of an interface with 34 pages: a training page, 32 pages (one per animation)

Table 1
Summary statistics per partition and across partitions for age, gender, level of musical training, level of dance training, internal consistency, and perceptual variables of the online study

	Partition 1		Partition 2		Partition 3		Partition 4		All partitions	
	Mean [SD]	Range	Mean [SD]	Range	Mean [SD]	Range	Mean [SD]	Range	Mean [SD]	Range
Age, y	31.77 [11.37]	16 to 75	36.94 [10.47]	19 to 57	36.53 [9.63]	20 to 75	33.31 [11.09]	16 to 67	34.64 [10.84]	16 to 75
Female, n (%)	77 (71.30)		62 (57.41)		61 (56.48)		69 (63.89)		269 (62.27)	
Musical training, n (%)										
No training	26 (24.07)		20 (18.52)		20 (18.52)		25 (23.15)		91 (21.06)	
1–3 years	27 (25)		28 (25.93)		26 (24.07)		29 (26.85)		110 (25.46)	
3–5 years	20 (18.52)		27 (25)		21 (19.44)		20 (18.52)		88 (20.37)	
5–10 years	13 (12.04)		8 (7.41)		12 (11.11)		18 (16.67)		51 (11.81)	
10 or more years	22 (20.37)		25 (23.15)		29 (26.85)		16 (14.81)		92 (21.30)	
Dance training, n (%)										
No training	43 (39.81)		32 (29.63)		25 (23.15)		37 (34.26)		137 (31.71)	
1–3 years	20 (18.52)		26 (24.07)		24 (22.22)		27 (25)		97 (22.45)	
3–5 years	22 (20.37)		19 (17.59)		23 (21.30)		22 (20.37)		86 (19.91)	
5–10 years	14 (12.96)		18 (16.67)		19 (17.59)		14 (12.96)		65 (15.05)	
10 or more years	9 (8.33)		13 (12.04)		17 (15.74)		8 (7.41)		47 (10.88)	
Internal consistency, α										
Similarity	.75		.68		.72		.74		–	
Interaction	.74		.66		.63		.79		–	
Leadership	.35		.38		.57		.55		–	
Perceptual variables										
Similarity	56.92 [28.06]	0 to 100	53.74 [28.91]	0 to 100	53.77 [28.58]	0 to 100	55.15 [28.71]	0 to 100	54.89 [28.59]	0 to 100
Interaction	57.43 [26.96]	0 to 100	51.98 [28.01]	0 to 100	52.23 [27.72]	0 to 100	55.32 [27.21]	0 to 100	54.24 [27.57]	0 to 100
Leadership	53.89 [24.56]	0 to 100	50.02 [27.47]	0 to 100	49.44 [26.82]	0 to 100	50.05 [24.27]	0 to 100	50.85 [25.88]	0 to 100



Dyad	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪
2	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪
3	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨
4	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨
5	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧
6	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧
7	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦
8	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦	🟧	🟨	🟪	🟦

Fig. 3. Allocation of the 128 dyadic animations (16 musical stimuli × 8 dyads) into four partitions (each represented with a different color) for the online study.

presented in random order, and a final page with a brief questionnaire including demographic questions (age, nationality, gender, musical training, dance training). On the training page, participants were informed about the task as they went through a practice trial. Once participants felt ready to continue with the study, they moved to the actual experiment, in which they were presented a stick figure animation at a time. For each animation, which was played in loop mode, they were asked to use sliders to rate the extent to which they would agree or disagree with the following statements: “These dancers are dancing similarly to each other” and “These dancers are interacting with each other.” In addition, they were asked to rate with sliders the extent to which one of the dancers was leading and the other was following. Here, the extremes of the slider were labeled as “the [left/right] dancer is leading,” while the middle referred to “Neither dancer is leading.” Finally, raters were asked to provide further optional comments, for example, on the way the dancers were moving and interacting.

2.3.4. Processing of perceptual ratings

To balance the loss of control from not having participants in the lab, it was necessary to pay careful attention to participant data quality and to ensure balanced participant samples across different experiment partitions. Following concerns regarding studies involving online or unsupervised participant samples (Thomas & Clifford, 2017), we utilized a number of exclusion criteria to strengthen the validity of our study. As an initial step, we discarded 38 participants whose responses included spurious information, such as nonexistent nationalities. Next, within each partition, participants whose mean intersubject correlation for either similarity or interaction were more than two standard deviations below the grand mean were considered outliers and were discarded; this resulted in the removal of 13 participants across all partitions. Our next step involved matching raters from different partitions based on gender and age in order to obtain comparable partitions of equal sample size ($N = 108$), that is, equal to the size of the smallest partition. To do this, we applied the optimization procedure that is described in the Appendix (A.1.1). Final steps in the processing of the perceptual data

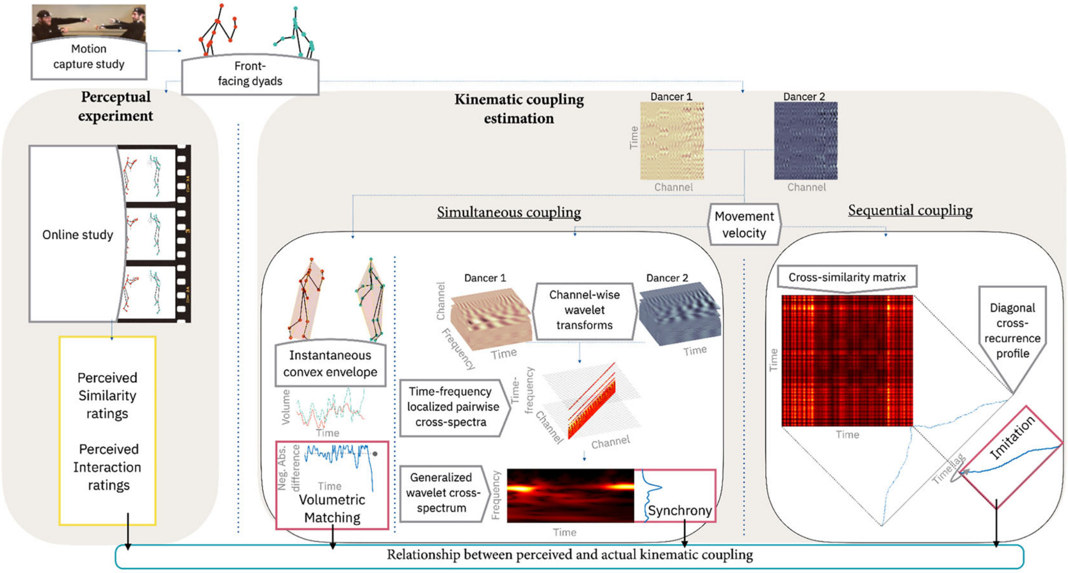


Fig. 4. Overall design of the study.

included computing partition-wise internal consistency (Cronbach's alpha) for each perceptual variable, and mean averaging the perceptual ratings across raters to get one average rating of each variable per animation.

2.4. Kinematic feature extraction

Three dyadic kinematic features were utilized in the study for prediction of perceived coupling (see Section 2.3.1); these features were used to quantify postural synchrony (*Volumetric Matching*), gestural simultaneous coupling (*Synchrony*), and gestural sequential coupling (*Imitation*). Additionally, another kinematic feature (*Orientation*) served for stimulus selection. A flowchart of the study design, with a focus on the investigated kinematic coupling features, is provided in Fig. 4. For the computation of the gestural coupling features (synchrony and imitation), we considered various possible methodological pipelines in order to ensure the stability of the results under variation and better understand observers' perceptual judgments. In this paper, we present a pipeline based on parameters that are validly applicable to both synchrony and imitation, ensure comparability between them and retain implementation simplicity. As regard our postural coupling feature (volumetric matching), we considered different implementations, such as approximating body size invariance by taking into account dancer height in the feature computation, but obtained optimal results with a more conventional approach based on previous work (e.g., Hachimura et al., 2005).

2.4.1. Orientation measure

A measure of frontal orientation between dyad members was computed for the full dataset of 1,440 recordings (after trimming the data to 8 s) to describe the degree to which the dancers were facing each other. The purpose of this step was to select 128 recordings from 8 dyads with high orientation for the perceptual study (see Section 2.3.1). Orientation was extracted from horizontal position data of dancers based on the calculation of the angles between the torso direction of each dancer and the torso position of the other dancer (see Hartmann et al., 2019 for a thorough description of the algorithm). Dyad-wise maximum torso orientation estimates across time were obtained using a 2-s moving window with half overlapping to provide a trade-off between resolution and localization given the length of the data.

2.4.2. *Movement data rotation*

A global coordinate system was employed to best record the trajectories of the individual markers affixed to the dancers; see Appendix (A.1.2) for an elaboration on this point. Due to horizontal rotations produced by the dancers' movements, a coordinate system transformation was applied such that dancers' corresponding movement directions could be effectively compared. Each dancer was rotated so as to have a frontal view in each frame; that is, we defined the mediolateral axis to be parallel to the segment joining the hip markers.

2.4.3. *Horizontal mirroring*

We investigated whether dancers mirrored each other's dance movements (see H4), assuming that observers would pay attention to these mirrored forms of coupling. This was operationalized by swapping joints along the sagittal plane and changing the sign of the mediolateral component for one of the dyad members (see Fujiwara & Daibo, 2022 for a similar procedure in a 2D space). This resulted in coupling estimates that were based, for example, on comparisons between the left arm of one dancer and the right arm of the other dancer. Main analyses were conducted with and without horizontal mirroring in order to estimate its relative importance.

2.4.4. *Volumetric Matching measure*

A rotation and translation invariant geometric descriptor was devised to quantify the degree of simultaneous postural coupling between the dancers (see H2 above). Using the MATLAB boundary() function, the convex envelope (or convex hull) volume enclosing the set of joints from each dancer's position data was calculated at each time point, following previous work (e.g., Ajili et al., 2019; Hachimura et al., 2005). Subsequently, the absolute difference in volume between dyad members was calculated at each time point. Finally, a temporal mean was obtained and the result was multiplied by -1 to describe similarity instead of dissimilarity between dancers; hence, the feature is bounded between $-\infty$ (no Volumetric Matching) and 0 (perfect Volumetric Matching or isovolumetry).

2.4.5. *Synchrony measure*

A time-frequency analysis method for estimating simultaneous dyadic coupling at multiple temporal scales (see H1 and H2 above) was applied to velocity data extracted from the 128 selected movement recordings; see Appendix (A.1.4) for an elaboration on the velocity computation. Synchrony is a vector of average coupling estimates across time at different movement frequencies.

The calculation of the generalized cross-wavelet transform involved a resampling of the frequency axis of the wavelet transforms to a beat-relative scale (ranging between half- and four-beat levels) as a means to obtain comparable synchrony estimates across stimuli of different tempi. To reach the largest beat level for the stimulus with the lowest tempo (97 BPM), we prepended 40 extra frames (⅔ of a second) to its corresponding movement data. Next, synchrony was obtained based on the calculation of a wavelet transform separately for each data channel (i.e., each combination of the three movement directions and 20 body parts, such as mediolateral torso) using default Matlab parameters in the *cwt()* function. A generalized cross-wavelet transform was obtained via comparisons between corresponding data channels; subsequently, the temporal mean of generalized cross-wavelet transform magnitudes was obtained, thus yielding a multivariate, plurifrequential measure of frequency locking between dancers; see Appendix (A.1.5) for an elaboration on the parameters applied to compute synchrony.

2.4.6. Imitation measure

To quantify the degree of sequential coupling between the dancers (see H1 and H2 above), imitation estimates were extracted from each dyadic movement recording. This time-delay analysis method provides information on the relationship between corresponding body parts and movement directions (i.e., channels) in the velocity data of the dancers at different absolute time lags. The approach is based on multidimensional cross-recurrence quantification analysis (MdCRQA, see Wallot, 2019); its major difference from MdCRQA is that imitation is based on a cross-similarity matrix instead of a cross-recurrence matrix, and thus, prescinds from a thresholding parameter for its calculation.

To compute imitation, a time-by-time cross-similarity matrix of dot products between the velocity data of the two dancers is first obtained. Next, the sum of each diagonal in the cross-similarity matrix is computed to obtain a time series describing the sum of cross-correlations between corresponding data channels, where each point represents the relationship between the dancers at a given time lag. Next, corresponding negative and positive lags are summed in order to obtain an estimate of sequential coupling between dancers for time delays ranging between 0 and 8 s. Finally, to make stimuli with different tempo comparable, imitation estimates were resampled to a beat lag scale ranging between 0 and 4 beats. A mathematical description of the imitation feature is provided in the Appendix (A.1.6) along with some of its properties.

2.5. Exploration of kinematic coupling estimates

As a preliminary step to the computation of correlations between perceived and kinematic coupling, we obtained summary statistics (i.e., mean and standard deviation) on the extracted features mainly to verify their similarity across partitions. Moreover, the same analysis was performed over an artificial set of coupling estimates. This set was generated by computing coupling estimates from each possible combination of dyad members dancing to the same stimulus. In addition, we separately examined full body coupling and the specific role of hand (i.e., wrist and finger) movements, following previous work that underscored the importance of hand movements on interaction and communication (Carlson et al., 2019; Goldin-Meadow, 2006). Analyses based on full body coupling were compared with those in which hand movements were removed before coupling estimation (see H3); this choice was motivated due to similarities in coupling magnitudes between full body and "no hands" coupling, thus more easily facilitating visual inspection than using the complementary "hands-only" option.

For gestural features, we conducted separate analyses for vertical and horizontal coupling (see H1), after previous work suggesting that body movements in different directions can simultaneously manifest diverging metrical levels in the music (Toiviainen et al., 2010) and that different coupling modalities such as visual and auditory might be displayed through distinct movement directions (Chauvigné et al., 2019). Also, we further examined the variation of the gestural kinematic features (synchrony and imitation) at different beat levels and lags.

Subsequently, nonparametric tests were carried out to investigate possible differences between coupling estimates from genuine and pseudodata (see H5 above; see Fujiwara & Daibo, 2022) and to estimate the contribution of hand movements to coupling.

2.6. *Correlation between perceived and actual coupling*

Pearson correlations were computed in order to understand the relationship between observers' judgments of coupling and the kinematic coupling estimates. Analyses were separately carried out for full body and "no hands" coupling (see H3 above). For gestural features, these analyses were performed separately at different beat levels and beat lags, and for vertical and horizontal directions (see H1 above); in addition, hand coupling (see H3 above) and the effects of horizontally mirroring the movement data (see H5 above) were explored. Nonparametric Mann–Withney U-tests tests were used to examine possible differences between similarity and interaction with respect to their correlations with the coupling features. For gestural coupling, possible effects of beat levels and lags upon the correlations were also investigated through nonparametric tests.

3. Results

3.1. *Perceptual study sample and ratings*

Demographic characteristics of the sample of participants selected from the perceptual study are presented in Table 1 separately for each partition and also across partitions. Internal consistency analyses reached values usually considered acceptable (Taber, 2018) for similarity and interaction, but not for leadership. Therefore, the leadership variable was left out of the analysis. According to mean ratings across the data from all partitions, the highest rated variable was Similarity, closely followed by Interaction. A strong correlation was observed between similarity and interaction, $r(126) = .72, p < .001$.

3.2. *Kinematic coupling estimates*

Computational coupling estimates were analyzed through summary statistics and correlations with perceptual ratings. For gestural coupling, our analyses focused mainly on beat

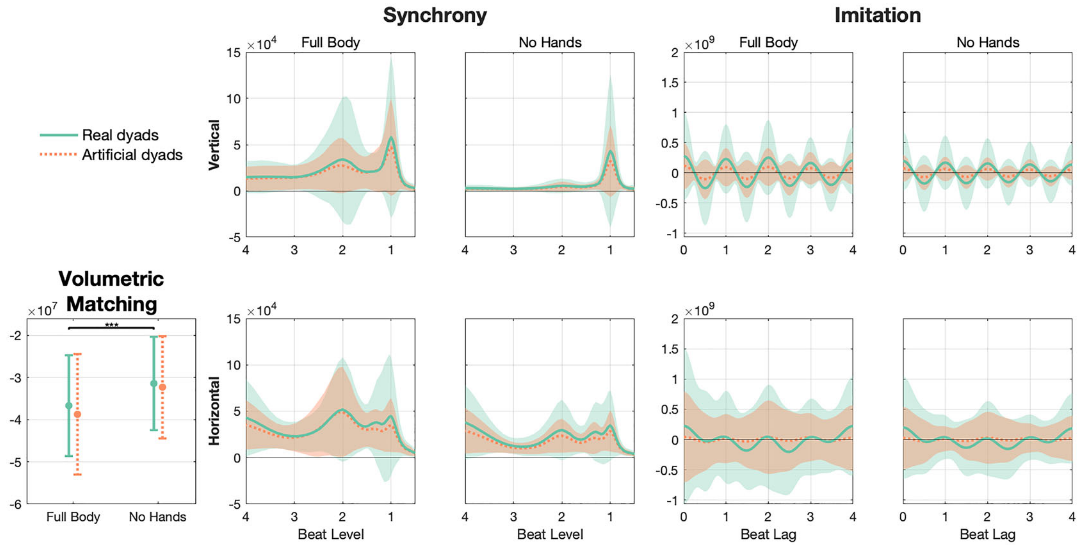


Fig. 5. Mean coupling estimates for full body and "no hands" analyses of volumetric matching, vertical and horizontal synchrony, and vertical and horizontal imitation. Coupling estimates were calculated for 128 real (green) and 1792 artificial (red) dyads. Filled areas denote ±1 SD.

levels and lags associated with the musical metrical structure, namely, 1-, 2-, and 4-beat levels for synchrony and 0-, 1-, 2-, and 4-beat lags for imitation. Except when otherwise stated, dancer's joints were horizontally mirrored before computing gestural coupling features (synchrony and imitation). Supporting Information Table A1 presents summary statistics per partition and across partitions for all the extracted descriptors. Correlations between coupling estimates (synchrony, imitation, and volumetric matching) are presented in Supporting Information Table A2 (vertical gestural coupling) and Supporting Information Table A3 (horizontal gestural coupling).

Summary statistics of the kinematic coupling measures were obtained to verify similarity in kinematic coupling across different partitions. Additionally, they allowed to compare coupling between real and artificial dyads, and for gestural coupling features, to estimate whether the coupling tended to be in- or antiphase, whether it followed the musical meter, to understand the impact of hand movements upon coupling, and to describe coupling at different movement directions, beat levels, and lags of interest.

Fig. 5 shows mean and standard deviation volumetric matching, synchrony (between 4- and $\frac{1}{2}$-beat levels), and imitation (between 0- and 4-beat lags) for both real dyads (green) and artificial dyads (red). One-tailed Mann–Whitney U-tests were computed to determine whether median full body coupling feature values were significantly higher for real dyads than artificial dyads. For gestural features, these tests were computed for vertical and horizontal directions and at beat lags and levels of interest. Regarding imitation, since it is a signed measure carrying information about phase differences between dyad members, absolute values were calculated to obtain unimodal distributions for this test. We observed higher full body mean

(Fig. 5) and median (Supporting Information Table A4) coupling for real dyads than for artificial dyads, with the exceptions of median vertical and horizontal synchrony at a 4-beat level. Imitation magnitudes yielded significant differences at various beat lags, especially for horizontal coupling. For both movement directions, we observed cosine-like Imitation profiles (Fig. 5), indicating that dyadic coupling was generally in-phase; for artificial dyads, these profiles were closer to zero, denoting lower, and more antiphase, coupling between dancers. For gestural features, mean feature values tended to increase around beat levels and lags of interest regardless of whether the dyads were real or artificial. Full body synchrony peaks were largest at 1-, 2-, and 4-beat levels. As regards full body Imitation, mean values across dancers were highest at integer beat lags for vertical coupling and at 0- and 4-beat lags for horizontal coupling.

To inspect the specific contribution of hands upon full body coupling, full body analyses were compared with those in which the hands were removed. For postural coupling (Fig. 5), according to a two-tailed Mann–Whitney U-test, volumetric matching was significantly higher for “no hands” ($\mathrm{Mdn}/10^7 = -2.93$) than for full body analyses ($\mathrm{Mdn}/10^7 = -3.45$), $U/10^5 = 0.11$, $p < .001$; this result was expected because limb movements increase the number of degrees of freedom of the estimated volumes. As regards gestural coupling (Supporting Information Table A5), estimates were higher for full body than for “no hands” analyses, reaching statistical significance in all cases except for 1-beat-level horizontal synchrony. While these differences can be attributed to larger velocity magnitudes for hand movements than for other body parts, it can be noted that the largest observed differences, observed at 2-beat-level synchronous vertical coupling, are most likely due to patterns of interlimb coupling, whereby reciprocal, out of phase hand motions are maintained throughout the dance.

3.3. *Correlation between coupling estimates and perceptual ratings*

The relationship between kinematic and perceived coupling was studied to understand the prediction ability of the proposed features and their relative accuracy with respect to other coupling measures, and to examine the relative impact of different perceptual variables upon the prediction accuracy. For gestural coupling features, these analyses also helped to assess the contribution of different coupling time scales and delays, hand movements, and horizontal mirroring to prediction.

Correlations between perceptual variables and coupling features are presented as nine analyses in Fig. 6. A percentile bootstrapped method with 10,000 iterations was applied to generate a 95% confidence interval (shown with error bars in Fig. 6). The majority of these correlations reached statistical significance (at least at one-tailed $p < .05$), based on both one-tailed hypothesis testing using Student’s t-distribution and on nonparametric bootstrapping. Regarding correlations between volumetric matching and the perceptual features, larger effect sizes were obtained for similarity than for interaction. Correlations between full body volumetric matching and similarity were the largest observed in this study for that perceptual variable, $r(128) = .40$, one-tailed $p < .001$; in contrast, no relationship was found for Interaction, $r(128) = .14$, one-tailed $p = .11$. The “no hands analysis” yielded some prediction increase for both perceptual variables, that is, $r(128) = .41$, one-tailed $p < .001$ for Similarity

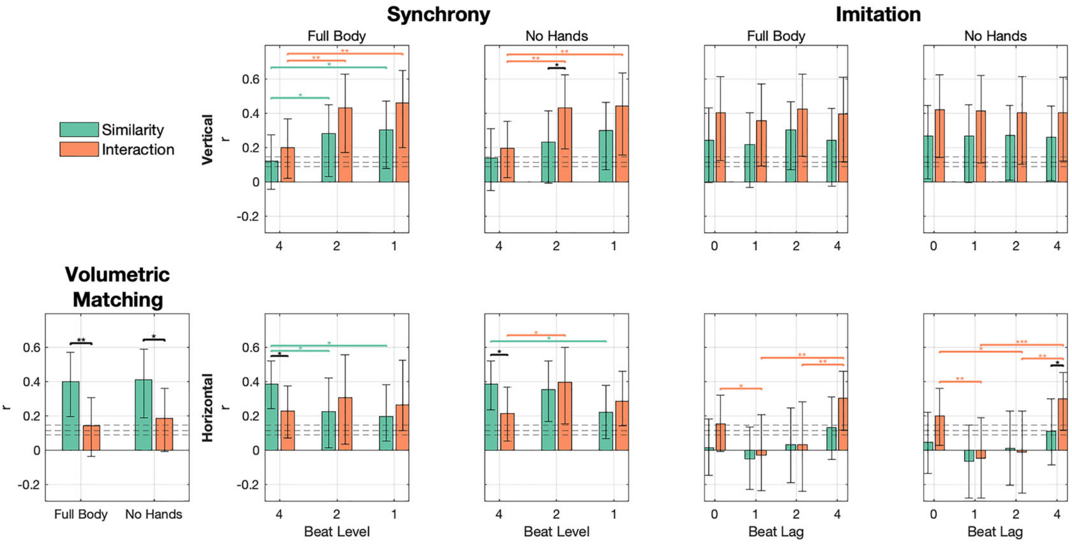


Fig. 6. Pearson correlations between perceptual variables (similarity and interaction) and coupling estimates (volumetric matching, synchrony, and imitation). Correlations with gestural features (synchrony and imitation) are presented at horizontal and vertical movement components and at selected beat levels and beat lags. Error bars indicate bootstrapped 95% confidence intervals (10,000 iterations). Dashed lines indicate, from bottom to top, one-tailed $p < .05$, $p < .01$, and $p < .001$ significance levels (uncorrected for multiple comparisons). $N = 128$.

and $r(128) = .19$, one-tailed $p < .05$ for Interaction. As regards gestural features, synchrony yielded relatively high correlations for both similarity ($r(126) = .39$, one-tailed $p < .001$ for full body horizontal coupling at a 4-beat level), and interaction ($r(126) = .46$, one-tailed $p < .001$ for full body vertical coupling at a 1-beat level), outperforming, together with volumetric matching, state-of-the-art and baseline coupling measures (Supporting Information Figure A1). Correlations with Imitation were, in contrast, lower for Similarity (peaking at $r(126) = .30$, one-tailed $p < .001$ for full body vertical coupling at a 2-beat lag) but reached comparable values for Interaction ($r(126) = .42$, one-tailed $p < .001$, also for 2-beat lag full body vertical coupling).

Next, we investigated possible differences between the obtained correlations (Fig. 6). For volumetric matching, we compared the perceptual features based on their correlation with the kinematic coupling estimates (significant differences shown with black horizontal segments). Correlations with similarity were significantly higher (one-tailed $p < .05$) than those obtained with interaction. For gestural features, two types of comparisons were performed to assess differences between correlations in each analysis: different perceptual variables were compared at a same beat level/lag (significant differences shown with black horizontal segments) and different beat levels/lags were compared for a same perceptual variable (significant differences shown with colored segments). In all cases, vertical coupling exhibited higher prediction for interaction than for similarity (as shown in Fig. A2, this was also observed for a larger sequence of beat levels and around integer beat lags, that is, those associated with in-phase coupling). For the “no hands” analysis, these differences reached statistical significance around a 2-beat level (ranging between ∼1.5 and ∼3, see Fig. A2). This direction of results (i.e., higher prediction for interaction than for similarity) was also observed with horizontal Imitation at a 0-beat lag and at a 4-beat lag, reaching statistical significance (one-tailed $p < .05$) in the latter (“no hands” analysis). In contrast, horizontal synchrony yielded significantly higher (one-tailed $p < .05$) correlations with similarity than with interaction; this was observed both for full body and “no hands.”

Regarding differences between beat levels/lags of gestural features, correlations with vertical synchrony tended to be significantly higher at faster beat levels (1 and 2) than at the 4-beat level. For horizontal synchrony, correlations with Similarity were significantly higher at the 4-beat level than at other beat levels of interest. Correlations with interaction, in contrast, were highest at the 2-beat level, reaching significant differences between 2- and 4-beat levels for the “no hands” analysis. As regards imitation, correlation profiles at beat lags of interest were rather constant for vertical trajectories, whereas in the horizontal plane, these were dependent on the beat lag, exhibiting significantly larger coefficients at 0- and 4-beat lags than at other lags.

Regarding the prediction of similarity, two simultaneous coupling features yielded best results, namely, volumetric matching ($r(126) = .40$, one-tailed $p < .001$) and full body horizontal synchrony ($r(126) = .39$, one-tailed $p < .001$) at a 4-beat level. A multiple linear regression was calculated to predict similarity from these two coupling features (Similarity ∼ 1 + Volumetric Matching + 4-beat level Horizontal Synchrony). This calculation was motivated by the low correlation observed between the independent variables ($r(126) = .19$, $p < .05$), ruling out collinearity between them. A significant regression equation was found ($F(2,125) = 21.755$, $p < .001$) with an R^2 of .258 (adjusted $R^2 = .246$). Standardized beta coefficients were similar for both predictors (volumetric matching ß = .34, 4-beat-level horizontal synchrony ß = .32), suggesting a similar contribution of both predictors to the model.

3.3.1. *Hand coupling*

As shown in Fig. 6, the removal of hand movement data from the analysis did not make a relevant impact on the aforementioned correlations between the perceptual variables and the kinematic features. For volumetric matching, the correlations for the “no hands” analysis were slightly higher, suggesting that hand movements decrease the accuracy of the postural coupling estimates. For gestural features, the removal of hand movement data did not make a clear difference in the correlations at beat levels and lags of interest. Comparing “hands only” with “no hands” analyses (see Supporting Information Figure A3), however, higher correlations were observed in the “hands only” analysis for synchrony at around the $\frac{1}{2}$-beat level, especially with interaction. Apart from this, correlations were either similar or lower for “hands only” compared to “no hands” analyses. For vertical imitation, correlation decreased at odd beat lags for the full body (Supporting Information Figure A2) and “hands only” (Supporting Information Figure A3) analyses; these were expected due to alternating 2-beat hand movement patterns.

It should be noted that horizontal synchrony reached a correlation peak at around a 1.5-beat level (Supporting Information Figures A2 and A3); an additional investigation revealed that

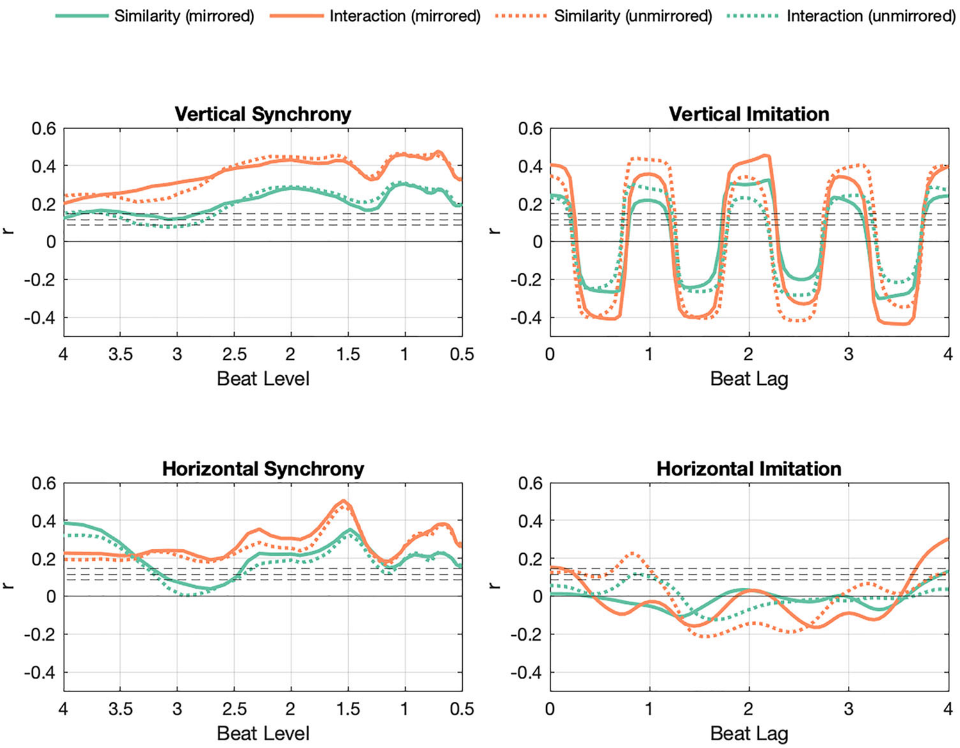


Fig. 7. Beat-level and lag-wise Pearson correlations between perceptual variables (similarity and interaction) and gestural coupling estimates (synchrony and imitation) for horizontal and vertical movement components at selected beat levels and beat lags. Solid and dashed colored lines refer to correlations with coupling estimates based on mirrored and unmirrored body parts, respectively. Dashed gray lines indicate, from bottom to top, one-tailed $p < .05$, $p < .01$, and $p < .001$ significance levels (uncorrected for multiple comparisons). $N = 128$.

the peak gets flattened if not only fingers and wrists but also elbows are removed (other than that, no salient differences were found between results obtained from “no hands” and “no arms” analyses). This peak is likely to be associated with variability in velocity periods and amplitudes of the limbs, which make a relatively large contribution to the coupling estimates due to larger velocity magnitudes.

3.3.2. *Mirroring effects*

The effect of horizontally mirroring the dancers’ movement data prior to the computation of gestural coupling features (synchrony and imitation) was examined. As shown in Fig. 7, correlation profiles for synchrony were highly similar. For imitation, in contrast, the mirrored analysis yielded higher correlations at beat lags 0 and 2, whereas the opposite is found at beat lags 1 and 3. This pattern suggests that dyads perceived as highly coupled tend to mirror their movements more and vice versa: as is to be expected for dyads mirroring their movements, increased correlations are observed at even beat lags due to in-phase relations between the compared body parts, whereas the correlation decreases at odd lags due to antiphase coupling between the dancers' corresponding bilateral body parts.

4. Discussion

Our investigation focused on the prediction of judgements of perceived coupling between partner-facing dancing dyads using postural and gestural kinematic estimates describing synchronous and sequential coupling. Perceptual ratings obtained from observers watching silent stick figure animations of dancing dyads were predicted using three coupling features, namely, volumetric matching, synchrony, and imitation, which were extracted from the corresponding kinematic data. Volumetric matching is a postural measure based on differences in the instantaneous convex envelope of the dancers. It offers a rotation and translation invariant description of dyadic coupling based on the degree of simultaneous congruence between dancers' postures. Regarding gestural measures, synchrony is a set of simultaneous coupling estimates at a spectrum of temporal scales, whereas imitation involves both isochronous and, mainly, time-delayed estimates of coupling. Synchrony, as a period locking spectrum, makes it possible to assess the relative contribution of different movement frequencies to dyadic coupling, helping to understand whether the dancers are mainly coupled through slow swaying, fast bouncing, or a combination thereof. Imitation, on the other hand, can help to identify leader–follower relationships or reciprocal exchanges of information; previous work has utilized similar features to quantify dance synchronization using parameterized (binarized) accounts of coupling between dancers (Crone et al., 2021), whereas our implementation is parameter-free. The main methodological contribution of this study was to carry out a perceptual validation of these three features.

The results of this study yielded either full or partial support for most of our stated hypotheses. Regarding H1, we did observe vertical coupling to be concentrated at faster frequencies and horizontal coupling to be more distributed along different time scales, but correlations with perceptual ratings only followed the expected results for vertical coupling. Following H2, we observed relationships between both simultaneous coupling features and similarity, on one hand, and between sequential coupling and interaction, on the other hand; regarding gestural features, the former relationships were observed only for horizontal coupling, while the latter were exhibited by both horizontal and vertical coupling. We failed to find support for H3, since we obtained similar prediction accuracy regardless of whether hand coupling information was removed or not from a full body coupling analysis, with the caveat that hands seemed to contribute to higher correlations with interaction at faster beat levels. In contrast, our findings supported H4, because dyads who were horizontally mirrored with each other were given higher ratings of similarity and interaction, and vice versa. Finally, H5 could be supported, since real dyads exhibited higher coupling than artificially matched ones, especially for horizontal imitation.

In addition to the above, gestural coupling analysis yielded two other relevant findings. First, we found links between interaction and faster coupling, and between similarity and slower coupling. Specifically, interaction was mainly related to faster (especially vertical) synchrony, and accurately predicted by both simultaneous and sequential gestural coupling features; further, for vertical coupling, interaction was better predicted than similarity regardless of the gestural coupling algorithm used. Similarity, in contrast, was better predicted than interaction only with slower horizontal simultaneous coupling. Another noteworthy finding was that real dyads exhibited higher mean coupling than artificially generated dyads for all the analyzed coupling features. This result shows that while entrainment to the music has a large impact upon coupling, social entrainment also makes a contribution to postural and gestural (especially sequential and synchronous horizontal) coupling.

The observed results are generally in accordance with our first hypothesis. As shown in Fig. 5, mean vertical coupling seemed to be mainly associated with 1- and 2-beat movements (i.e., at frequencies closer to the musical tactus level), possibly as a manifestation of the discrete musical beat signal, whereas mean horizontal coupling followed a somewhat less localized pattern (i.e., more distributed along multiple temporal scales), even after removing hand movement data from the analysis. Also, as shown in Fig. A2, correlation profiles reached a ceiling with vertical synchrony between around 1- and 2-beat levels, whereas correlations with horizontal synchrony yielded various local peaks at diverse beat lags. Overall, these results resonate with previously suggested relations between vertical movements and entrainment to discrete information (auditory beats) and between movements on the horizontal plane and entrainment to continuous (visual) information (Chauvigné et al., 2019).

Our second hypothesis proposed simultaneity–similarity and sequentiality–interaction associations. In accordance to this hypothesis, volumetric matching was found to be more highly associated with similarity than with interaction, suggesting that people pay attention to postural synchronous coupling when rating similarity. In partial accordance with the hypothesis, expected results were observed for gestural coupling estimates (Fig. 6), yet in the horizontal plane. According to these results, when rating similarity, people's perceptions may have been influenced by horizontal simultaneous coupling, whereas when rating Interaction these may have been influenced more by horizontal sequential coupling. Regarding vertical coupling, however, both synchrony (especially faster synchrony) and imitation yielded maximum correlations with interaction. It should be noted here that the maximum correlations between synchrony and similarity, which highlight faster vertical coupling and slower horizontal coupling, are consistent with previous findings underscoring the hierarchical structure of spontaneous dance movement, and specifically the relations between vertical movement and musical tactus and between horizontal movement and slow metric levels (Burger, London, Thompson, & Toiviainen, 2018; Toiviainen et al., 2010).

The synchrony coupling measure yielded one of the clearest results in the study, which is the association between fast vertical coupling and Interaction on one hand, and between slow horizontal coupling and Similarity on the other hand. Indeed, significant differences in Fig. 6 suggest for synchrony a link between interaction and faster vertical coupling (i.e., up to around 2 beats), and an association between similarity and slower horizontal coupling (especially around the 4-beat level). This relationship between fast vertical simultaneous coupling and interaction suggest that people pay attention to short mutual exchanges of information when rating interaction; in contrast, the link between slow horizontal simultaneous coupling and similarity might mean that similarity refers to a longer term stability in the coupling between dancers—this latter point being reinforced by the observed relationship between Volumetric Matching and Similarity. It should be highlighted at this point that similarity and interaction are correlated variables, which had already been noted in previous work (Hartmann et al., 2019). Our results provide new insights into the nuances between these perceptual dimensions.

A number of remarks could be made regarding Imitation. First, significant differences between selected beat lags were observed on the horizontal plane (Fig. 6), highlighting its slower periodicity and the relative importance of horizontal coupling through swaying over shorter anteroposterior and mediolateral movements. Second, while leadership had to be dropped from the analysis due to low internal consistency, this was not the case for interaction, which yielded relatively high correlations with imitation. While observers may not be able to distinguish leaders from followers in free dance movement, it is reasonable to wonder whether perception of reciprocal, bidirectional exchanges of information might be at stake, whereby dancers would constantly engage in mutual adaptation (Gallotti, Fairhurst, & Frith, 2017). A third remark is that time-delayed relationships (i.e., at lags other than 0) between perceived and kinematic coupling were for some analyses stronger than immediate relationships (i.e., at 0 lag), as shown in Supporting Information Figure A2 for both similarity and interaction; this can be clearly seen for horizontal imitation, where 4-beat lag correlations are higher than those at 0-beat lag. These results support the notion of nonsynchronous action mirroring (see Crone et al., 2021) and that observers paid attention to these aspects when rating Interaction. Further, they recall von Zimmermann, Vicary, Sperling, Orgs, and Richardson (2018) finding that distributed (time-delayed) coordination rather than unitary coordination predicted group bonding between dancers.

The role of hands in dyadic coupling remains unresolved. Although previous work suggested that people pay attention to hands when rating perceived synchrony (Carlson et al., 2019), our findings suggest that hand coupling did not make a clear impact on the prediction of perceived coupling and do thus not support the third hypothesis. However, we found hand mirroring to be more frequent among dancers who exhibit higher coupling, and vice versa (see below). Also, significant differences between interaction and similarity in their correlation with synchrony at beat levels between $\sim$1.5 and $\sim$3 for “no hands” analyses (Supporting Information Figure A2) are noteworthy. Since these differences seem to mainly relate to an increase in the correlations with similarity for the “no hands” analysis, these results could suggest increased attention from raters toward hand synchrony when rating similarity than when rating interaction. It shall be noticed too that the “hands only” analysis yielded higher correlations with interaction at faster (especially vertical) beat levels, suggesting that hand coupling plays a role in the association between interaction and faster vertical coupling (Supporting Information Figure A3). It is also worth pointing out that, comparatively, there is a greater variety of possible and likely hand and upper limb movements dancers could be making compared to other parts of the body, making it difficult to fully explore their perceptual influence in a single study. Overall, the contribution of hand movements on perceived coupling deserves further investigation in order to clarify these mixed results.

Regarding mirroring effects, and in connection with our fourth hypothesis, correlations with imitation and with horizontal synchrony (Fig. 7) suggest that dyads who tended to mirror at least some of their movements—hand movements in particular—were given higher coupling ratings. Hence, these results suggest that people pay attention to horizontal mirroring when rating dyadic coupling. Associated with this result, according to the sign of mean feature values for Imitation at integer beat lags (Fig. 5), in-phase coupling is more common than antiphase coupling. Hence, the mirroring effects for sequential coupling are evident both through the correspondence between bilateral body parts and the overall pattern of phase relations. Finally, it is interesting to note that for vertical synchrony, there is no clear effect of mirroring (Fig. 7). This suggests that simultaneous vertical coupling is a relatively weak descriptor of social entrainment, an interpretation that is reinforced by the relatively low differences between artificial and real dyadic coupling estimates for vertical synchrony (Fig. 5).

Disentangling nonsocial rhythmic entrainment from social entrainment to understand their relative contributions to perceived coupling is a challenging problem that pervades the joint action literature (Marsh, Richardson, & Schmidt, 2009). In this respect, our results show that the predictability of perceived dance coupling from kinematic dance coupling increases when the latter is evaluated at temporal scales that follow the structural hierarchy of the music danced to. Indeed, repetitive movements following the musical tactus, such as bouncing, might be important predictors of perceived coupling even if these could be, for instance, better characterized as self-imitation than as other-imitation. However, rhythmic entrainment does not suffice to explain the perceptual responses, as suggested by the higher coupling (significantly higher for sequential coupling) estimates obtained from real dyads than from artificially coupled ones, which are in accordance with our fifth hypothesis. In other words, the dyadic movement coupling studied here cannot be reduced to the incidental similarity between dancers sharing a similar representation of a task (rhythmic entrainment to music); more importantly, it reflects the activity of a higher level structure (i.e., an interpersonal synergy) that is supported by the, for example, visual coupling of the dancers' degrees of freedom (see, e.g., Dale, Fusaroli, Duran, & Richardson, 2013; Fusaroli, Rączaszek-Leonardi, & Tylén, 2014; Riley et al., 2011; Schmidt & Fitzpatrick, 2016). In this respect, previous work has found that joint movements can be truly coordinated, reciprocal actions, and not just the result of executing similar yet independent motor programs due to shared task representations (Riley et al., 2011).

Although our results help to clarify the differences between nonsocial rhythmic and social entrainment, perceptual ratings of dancing pseudodyads would be needed for a thorough investigation of the perceptual impact of social entrainment in dance. This approach, introduced by Bernieri et al. (1988) but rarely reported in the literature, would allow to understand whether—and under what conditions—pseudointeractions are perceived as less coupled than their associated real interactions. Such an investigation could be enriched by including explicit leader-followership roles to elucidate the distinction between synchronous and sequential social entrainment.

The results of this study underscore the importance of multivariate methods for the study of human motoric coupling, which is multidimensional in nature. At least in dance research, both individual rhythmic entrainment and social coupling studies have often been based on the analysis of a single marker (Brown & Meulenbroek, 2016; Ellamil, Berson, Wong, Buckley, & Margulies, 2016; Shimizu & Okada, 2021; Solberg & Jensenius, 2019; von Zimmermann et al., 2018) or a single-body region (Sato, Nunome, & Ikegami, 2014) per dancer. However, different types of multivariate approaches, including latent space (Hartmann et al., 2019) and time-frequency analysis (Toiviainen & Hartmann, 2022) methods, have shown to outperform univariate ones such as correlations between vertical head velocities. Moreover, it must be stressed that multivariate (and multiscale) methods are important for the study of multiple coupling modalities (such as movement, respiration and heart rate, and gaze) and their interactions (Dale et al., 2013); current logistical and technical challenges to data collection are likely to be solvable, and costs are likely to reduce. The rarity of whole-body (Chang et al., 2020) and multimodal perspectives integrating behavioral, cognitive, and contextual factors sets an agenda for future research.

A potential limitation of this study is its explanatory power, which suffers from the summarization of perceptual ratings. The applied procedure aimed to obtain equal-sized, age- and gender-balanced groups to avoid possible confounders but might have failed to accommodate differing baselines and ranges of ratings from participants or participant groups. As a suggestion for further research, the contribution of variables of interest such as gender and age of observers to the prediction of perceived coupling could be accounted for and understood by means of multilevel modeling approaches.

Another goal for further research would be to understand the possible contribution of fine-grained movements, such as those conveyed via facial and hand expressions, to dyadic dance coupling and its perception. Novel pose estimation techniques that do not require the use of motion capture markers (e.g., Cao et al., 2017) might help in clarifying the unique contribution of these subtle yet significant gestures.

To conclude, this study tackled the issue of perceived similarity and interaction in dance. While previous studies on the subject highlighted the importance of mutual gaze upon perceived dyadic coupling (Carlson et al., 2019; Hartmann et al., 2019), we focused on front-facing dyadic animations and proposed novel kinematic features to assess the contribution of other factors. According to our results, similarity seems to relate to both gestural synchrony (specifically, to simultaneous slow horizontal sway) and to postural synchrony (specifically, to similar bounding volume dynamics), whereas interaction is more associated with faster gestural synchrony and with Imitation. As a methodological contribution, we have perceptually validated three novel approaches to model kinematic coupling, which is a complex dynamical process whose lack of standardized quantification methods (Ayache et al., 2021) is shared with neighboring research realms (Cliff, Lizier, Tsuchiya, & Fulcher, 2022). Multivariate analysis techniques can help to clarify the perception of movement coupling and other issues both inside and outside the realm of music-induced movement. The present study represents a step further in the understanding of perceived similarity and interaction in dance coupling and opens up new avenues for explaining the distinction between rhythmic and social entrainment. In conclusion, the free dance paradigm can provide significant insights into human perception and joint action.

Declaration of competing interest

None.

Note

1 The term "coupling" is chosen here as it denotes fewer connotations than, for example, "coordination" and does not necessarily imply an exchange of information between individuals (Dumas & Fairhurst, 2021). This usage of the term should not be confused with the coupling parameters used in dynamic models of movement coordination, such as the HKB model (Haken, Kelso, & Bunz, 1985).

References

Ajili, I., Ramezanpanah, Z., Mallem, M., & Didier, J.-Y. (2019). Expressive motions recognition and analysis with learning and statistical methods. *Multimedia Tools and Applications*, *78*(12), 16575–16600. https://doi.org/10.1007/s11042-018-6893-5

Ayache, J., Connor, A., Marks, S., Kuss, D. J., Rhodes, D., Sumich, A., & Heym, N. (2021). Exploring the "Dark Matter" of social interaction: Systematic review of a decade of research in spontaneous interpersonal coordination. *Frontiers in Psychology*, *12*, 4447. https://doi.org/10.3389/fpsyg.2021.718237

Bamford, J. S., Burger, B., & Toiviainen, P. (2023). Turning heads on the dance floor: Synchrony and social interaction using a silent disco paradigm. *Music & Science*, *6*, 20592043231155416.

Bernardis, P., & Gentilucci, M. (2006). Speech and gesture share the same communication system. *Neuropsychologia*, *44*(2), 178–190. https://doi.org/10.1016/j.neuropsychologia.2005.05.007

Bernieri, F. J., Reznick, J. S., & Rosenthal, R. (1988). Synchrony, pseudosynchrony, and dissynchrony: Measuring the entrainment process in mother-infant interactions. *Journal of Personality and Social Psychology*, *54*(2), 243–253. https://doi.org/10.1037/0022-3514.54.2.243

Brown, D. D., & Meulenbroek, R. G. J. (2016). Effects of a fragmented view of one's partner on interpersonal coordination in dance. *Frontiers in Psychology*, *7*, 614. https://doi.org/10.3389/fpsyg.2016.00614

Burger, B., London, J., Thompson, M. R., & Toiviainen, P. (2018). Synchronization to metrical levels in music depends on low-frequency spectral components and tempo. *Psychological Research*, *82*, 1195–1211. https://doi.org/10.1007/s00426-017-0894-2

Burger, B., & Toiviainen, P. (2013). Mocap Toolbox – A Matlab toolbox for computational analysis of movement data. In *Proceedings of the Sound and Music Computing Conference*, pp. 172–178.

Camurri, A., Lagerlöf, I., & Volpe, G. (2003). Recognizing emotion from dance movement: Comparison of spectator recognition and automated techniques. *International Journal of Human-Computer Studies*, *59*(1), 213–225. https://doi.org/10.1016/S1071-5819(03)00050-8

Cao, Z., Simon, T., Wei, S. E., & Sheikh, Y. (2017). Realtime multi-person 2D pose estimation using part affinity fields. In *Proceedings of the IEEE conference on computer vision and pattern recognition* (pp. 7291–9).

Carlson, E., Burger, B., & Toiviainen, P. (2019). Empathy, entrainment, and perceived interaction in complex dyadic dance movement. *Music Perception: An Interdisciplinary Journal*, *36*(4), 390–405. https://doi.org/10.1525/mp.2019.36.4.390

Carlson, E., Saari, P., Burger, B., & Toiviainen, P. (2017). Personality and musical preference using social-tagging in excerpt-selection. *Psychomusicology: Music, Mind, and Brain*, *27*3, 203–212. https://doi.org/10.1037/pmu0000183

Chang, M., Halaki, M., Adams, R., Cobley, S., Lee, K.-Y., & O'Dwyer, N. (2016). An exploration of the perception of dance and its relation to biomechanical motion: A systematic review and narrative synthesis. *Journal of Dance Medicine & Science*, *20*(3), 127–136. https://doi.org/10.12678/1089-313X.20.3.127

Chang, M., O'Dwyer, N., Adams, R., Cobley, S., Lee, K.-Y., & Halaki, M. (2020). Whole-body kinematics and coordination in a complex dance sequence: Differences across skill levels. *Human Movement Science*, *69*, 102564. https://doi.org/10.1016/j.humov.2019.102564

Chartrand, T. L., & Bargh, J. A. (1999). The chameleon effect: The perception–behavior link and social interaction. *Journal of Personality and Social Psychology*, *76* (6), 893–910. https://doi.org/10.1037/0022-3514.76.6.893

Chauvigné, L. A. S., Walton, A., Richardson, M. J., & Brown, S. (2019). Multi-person and multisensory synchronization during group dancing. *Human Movement Science*, *63*, 199–208. https://doi.org/10.1016/j.humov.2018.12.005

Christensen, J. F., Cela-Conde, C. J., & Gomila, A. (2017). Not all about sex: Neural and biobehavioral functions of human dance. *Annals of the New York Academy of Sciences*, *1400*(1), 8–32.

Cliff, O. M., Lizier, J. T., Tsuchiya, N., & Fulcher, B. D. (2022). Unifying pairwise interactions in complex dynamics. *ArXiv:2201.11941 [Physics]*. http://arxiv.org/abs/2201.11941

Crone, C. L., Rigoli, L. M., Patil, G., Pini, S., Sutton, J., Kallen, R. W., & Richardson, M. J. (2021). Synchronous vs. non-synchronous imitation: Using dance to explore interpersonal coordination during observational learning. *Human Movement Science*, *76*, 102776. https://doi.org/10.1016/j.humov.2021.102776

Cross, I. (2001). Music, cognition, culture, and evolution. *Annals of the New York Academy of Sciences*, *930*(1), 18–42.

Dahl, S., & Friberg, A. (2007). Visual perception of expressiveness in musicians' body movements. *Music Perception*, *24*(5), 433–454.

Dale, R., Fusaroli, R., Duran, N. D., & Richardson, D. C. (2013). The self-organization of human interaction. In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 59, pp. 43–95). Amsterdam: Academic Press.

Dumas, G., & Fairhurst, M. T. (2021). Reciprocity and alignment: Quantifying coupling in dynamic interactions. *Royal Society Open Science*, *8*(5), 210138. https://doi.org/10.1098/rsos.210138

Dumas, G., Laroche, J., & Lehmann, A. (2014). Your body, my body, our coupling moves our bodies. *Frontiers in Human Neuroscience*, *8*, 1004.

Ellamil, M., Berson, J., Wong, J., Buckley, L., & Margulies, D. S. (2016). One in the Dance: Musical correlates of group synchrony in a real-world club environment. *PLoS One*, *11*(10), e0164783. https://doi.org/10.1371/journal.pone.0164783

Feniger-Schaal, R., & Lotan, N. (2017). The embodiment of attachment: Directional and shaping movements in adults' mirror game. *The Arts in Psychotherapy*, *53*, 55–63. https://doi.org/10.1016/j.aip.2017.01.006

Frith, C. D., & Frith, U. (2007). Social cognition in humans. *Current Biology*, *17*(16), R724–R732.

Fink, B., Bläsing, B., Ravignani, A., & Shackelford, T. K. (2021). Evolution and functions of human dance. *Evolution and Human Behavior*, *42*(4), 351–360. https://doi.org/10.1016/j.evolhumbehav.2021.01.003

Fujiwara, K., & Daibo, I. (2022). Empathic accuracy and interpersonal coordination: Behavior matching can enhance accuracy but interactional synchrony may not. *The Journal of Social Psychology*, *162*(1), 71–88.

Fusaroli, R., Rączaszek-Leonardi, J., & Tylén, K. (2014). Dialog as interpersonal synergy. *New Ideas in Psychology*, *32*, 147–157. https://doi.org/10.1016/j.newideapsych.2013.03.005

Gallotti, M., Fairhurst, M. T., & Frith, C. D. (2017). Alignment in social interactions. *Consciousness and Cognition*, *48*, 253–261. https://doi.org/10.1016/j.concog.2016.12.002

Goldin-Meadow, S. (2006). Talking and thinking with our hands. *Current Directions in Psychological Science*, *15*(1), 34–39. https://doi.org/10.1111/j.0963-7214.2006.00402.x

Grahn, J. (2012). See what I hear? Beat perception in auditory and visual rhythms. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *220*, 51–61. https://doi.org/10.1007/s00221-012-3114-8

Hachimura, K., Takashina, K., & Yoshimura, M. (2005). Analysis and evaluation of dancing movement based on LMA. In: *ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication, 2005*, pp. 294–299. https://ieeexplore.ieee.org/abstract/document/1513794, https://doi.org/10.1109/ROMAN.2005.1513794

Haken, H., Kelso, J. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, *51*(5), 347–356.

Hartmann, M., Mavrolampados, A., Allingham, E., Carlson, E., Burger, B., & Toiviainen, P. (2019). Kinematics of perceived dyadic coordination in dance. *Scientific Reports*, *9*(1), 15594. https://doi.org/10.1038/s41598-019-52097-6

Hu, Y., Cheng, X., Pan, Y., & Hu, Y. (2022). The intrapersonal and interpersonal consequences of interpersonal synchrony. *Acta Psychologica*, *224*, 103513. https://doi.org/10.1016/j.actpsy.2022.103513

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics*, *14*, 201–211.

Kenny, D. A. (1996). Models of non-independence in dyadic research. *Journal of Social and Personal Relationships*, *13*(2), 279–294.

Knoblich, G., & Sebanz, N. (2006). The social nature of perception and action. *Current Directions in Psychological Science*, *15*(3), 99–104.

Konzack, M., McKetterick, T., Ophelders, T., Buchin, M., Giuggioli, L., Long, J., … Buchin, K. (2017). Visual analytics of delays and interaction in movement data. *International Journal of Geographical Information Science*, *31*(2), 320–345. https://doi.org/10.1080/13658816.2016.1199806

Krauss, R. M., Chen, Y., & Chawla, P. (1996). Nonverbal behavior and nonverbal communication: What do conversational hand gestures tell us? In M. P. Zanna (Ed.), , *Advances in experimental social psychology* (Vol. 28, pp. 389–450). San Diego: Academic Press. https://doi.org/10.1016/S0065-2601(08)60241-5

von Laban, R., & Ullmann, L. (1966). *Choreutics*. London: Macdonald & Evans.

Lahnakoski, J. M., Forbes, P. A., McCall, C., & Schilbach, L. (2020). Unobtrusive tracking of interpersonal orienting and distance predicts the subjective quality of social interactions. *Royal Society Open Science*, *7*(8), 191815.

Lakin, J. L. (2013). Behavioral mimicry and interpersonal synchrony. In J. Hall & M. L. Knapp (Eds.), *Handbooks of communication science, Vol. 2: Nonverbal communication* (pp. 539–575). Boston: Mouton de Gruyter.

Lakin, J. L., Jefferis, V. E., Cheng, C. M., & Chartrand, T. L. (2003). The chameleon effect as social glue: Evidence for the evolutionary significance of nonconscious mimicry. *Journal of Nonverbal Behavior*, *27*(3), 145–162.

Laland, K., Wilkins, C., & Clayton, N. (2016). The evolution of dance. *Current Biology*, *26*(1), R5–R9.

Lee, H., Launay, J., & Stewart, L. (2020). Signals through music and dance: Perceived social bonds and formidability on collective movement. *Acta Psychologica*, *208*, 103093. https://doi.org/10.1016/j.actpsy.2020.103093

Lumsden, J., Miles, L. K., Richardson, M. J., Smith, C. A., & Macrae, C. N. (2012). Who syncs? Social motives and interpersonal coordination. *Journal of Experimental Social Psychology*, *48*(3), 746–751.

MacDougall, H. G., & Moore, S. T. (2005). Marching to the beat of the same drummer: The spontaneous tempo of human locomotion. *Journal of Applied Physiology*, *99*(3), 1164–1173. https://doi.org/10.1152/japplphysiol.00138.2005

Macpherson, M. C., Fay, N., & Miles, L. K. (2020). Seeing synchrony: A replication of the effects of task-irrelevant social information on perceptions of interpersonal coordination. *Acta Psychologica*, *209*, 103140. https://doi.org/10.1016/j.actpsy.2020.103140

Marsh, K. L., Richardson, M. J., & Schmidt, R. C. (2009). Social connection through joint action and interpersonal coordination. *Topics in Cognitive Science*, *1*(2), 320–339.

Mehr, S. A., Krasnow, M. M., Bryant, G. A., & Hagen, E. H. (2021). Origins of music in credible signaling. *Behavioral and Brain Sciences*, *44*, e60.

Merker, B. (2014). Groove or swing as distributed rhythmic consonance: Introducing the groove matrix. *Frontiers in Human Neuroscience*, *8*, 454. https://doi.org/10.3389/fnhum.2014.00454

Miles, L. K., Nind, L. K., & Macrae, C. N. (2009). The rhythm of rapport: Interpersonal synchrony and social perception. *Journal of Experimental Social Psychology*, *45*(3), 585–589. https://doi.org/10.1016/j.jesp.2009.02.002

Moulder, R. G., Boker, S. M., Ramseyer, F., & Tschacher, W. (2018). Determining synchrony between behavioral time series: An application of surrogate data generation for establishing falsifiable null-hypotheses. *Psychological Methods*, *23*(4), 757–773. https://doi.org/10.1037/met0000172

Muiños, M., & Ballesteros, S. (2021). Does dance counteract age-related cognitive and brain declines in middle-aged and older adults? A systematic review. *Neuroscience & Biobehavioral Reviews*, *121*, 259–276. https://doi.org/10.1016/j.neubiorev.2020.11.028

Phillips-Silver, J., & Keller, P. (2012). Searching for roots of entrainment and joint action in early musical interactions. *Frontiers in Human Neuroscience*, *6*26. https://doi.org/10.3389/fnhum.2012.00026

Ramezanpanah, Z., Mallem, M., & Davesne, F. (2020). Human action recognition using Laban movement analysis and dynamic time warping. *Procedia Computer Science*, *176*, 390–399.

Ravignani, A., & Cook, P. F. (2016). The evolutionary biology of dance without frills. *Current Biology*, *26*(19), R878–R879.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review*, *12*(6), 969–992.

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006-2012). *Psychonomic Bulletin and Review*, *20*(3), 403–452.

Riley, M., Richardson, M., Shockley, K., & Ramenzoni, V. (2011). Interpersonal Synergies. *Frontiers in Psychology*, 2. https://www.frontiersin.org/articles/10.3389/fpsyg.2011.00038

Sato, N., Nunome, H., & Ikegami, Y. (2014). Key features of hip hop dance motions affect evaluation by judges. *Journal of Applied Biomechanics*, *30*(3), 439–445. https://doi.org/10.1123/jab.2013-0190

Schmidt, R., & Fitzpatrick, P. (2016). The origin of the ideas of interpersonal synchrony and synergies. In P. Passos, K. Davids, and J. Y. Chow (Eds.), *Interpersonal Coordination and Performance in Social Systems*. Routledge.

Shimizu, D., & Okada, T. (2021). Synchronization and coordination of art performances in highly competitive contexts: Battle scenes of expert breakdancers. *Frontiers in Psychology*, *12*, 1114. https://doi.org/10.3389/fpsyg.2021.635534

Skipper, J. I., Goldin-Meadow, S., Nusbaum, H. C., & Small, S. L. (2007). Speech-associated gestures, Broca's area, and the human mirror system. *Brain and Language*, *101*(3), 260–277. https://doi.org/10.1016/j.bandl.2007.02.008

Solberg, R. T., & Jensenius, A. R. (2019). Group behaviour and interpersonal synchronization to electronic dance music. *Musicae Scientiae*, *23*(1), 111–134. https://doi.org/10.1177/1029864917712345

Taber, K. S. (2018). The use of Cronbach's alpha when developing and reporting research instruments in science education. *Research in Science Education*, *48*(6), 1273–1296. https://doi.org/10.1007/s11165-016-9602-2

Tarr, B., Launay, J., & Dunbar, R. I. M. (2016). Silent disco: Dancing in synchrony leads to elevated pain thresholds and social closeness. *Evolution and Human Behavior*, *37*(5), 343–349. https://doi.org/10.1016/j.evolhumbehav.2016.02.004

Thomas, K. A., & Clifford, S. (2017). Validity and mechanical turk: An assessment of exclusion methods and interactive experiments. *Computers in Human Behavior*, *77*, 184–197. https://doi.org/10.1016/j.chb.2017.08.038

Toiviainen, P., & Carlson, E. (2022). Embodied meter revisited: Entrainment, musical content and genre in music-induced movement. *Music Perception: An Interdisciplinary Journal*, *39*(3), 249–267.

Toiviainen, P., & Hartmann, M. (2022). Analyzing multidimensional movement interaction with generalized cross-wavelet transform. *Human Movement Science*, *81*, 102894. https://doi.org/10.1016/j.humov.2021.102894

Toiviainen, P., Luck, G., & Thompson, M. R. (2010). Embodied meter: Hierarchical eigenmodes in music-induced movement. *Music Perception*, *28*(1), 59–70. https://doi.org/10.1525/mp.2010.28.1.59

von Zimmermann, J., Vicary, S., Sperling, M., Orgs, G., & Richardson, D. C. (2018). The choreography of group affiliation. *Topics in Cognitive Science*, *10*(1), 80–94. https://doi.org/10.1111/tops.12320

Wallot, S. (2019). Multidimensional cross-recurrence quantification analysis (MdCRQA)–A method for quantifying correlation between multivariate time-series. *Multivariate Behavioral Research*, *54*(2), 173–191. https://doi.org/10.1080/00273171.2018.1512846

Washburn, A., DeMarco, M., de Vries, S., Ariyabuddhiphongs, K., Schmidt, R. C., Richardson, M. J., & Riley, M. A. (2014). Dancers entrain more effectively than non-dancers to another actor's movements. *Frontiers in Human Neuroscience*, *8*, 800. https://doi.org/10.3389/fnhum.2014.00800

Wass, S. V., Whitehorn, M., Marriott Haresign, I., Phillips, E., & Leong, V. (2020). Interpersonal neural entrainment during early social interaction. *Trends in Cognitive Sciences*, *24*(4), 329–342. https://doi.org/10.1016/j.tics.2020.01.006

Wiltermuth, S. S., & Heath, C. (2009). Synchrony and cooperation. *Psychological Science*, *20*(1), 1–5. https://doi.org/10.1111/j.1467-9280.2008.02253.x

Woolhouse, M. H., Tidhar, D., & Cross, I. (2016). Effects on inter-personal memory of dancing in time with others. *Frontiers in Psychology*, *7*, 167. https://doi.org/10.3389/fpsyg.2016.00167

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Online Appendix