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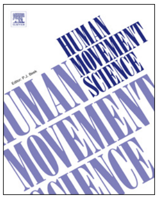

Multi-person and multisensory synchronization during group dancing

Léa A.S. Chauvigné[a], Ashley Walton[b], Michael J. Richardson[c], Steven Brown[a,*]

[a] *Department of Psychology, Neuroscience & Behaviour, McMaster University, Hamilton, Canada*
[b] *Department of Statistics, Harvard University, Boston, USA*
[c] *Department of Psychology and Perception in Action Research Centre, Faculty of Human Sciences, Macquarie University, Sydney, NSW, Australia*

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ABSTRACT

Synchronized group dancing is one of the hallmarks of both coordination and cooperation in the humans species. While a large amount of research has focused on joint action in dyads, the mechanisms of coordination in larger groups are not well understood. In the present study, we explored the coordination dynamics of a group of folk dancers by examining the influence of three sensory-coupling channels on the stability of group coordination. Using 3D motion capture, we recorded a group of 13 expert folk dancers performing to the beat of music (auditory coupling) while holding hands in a circle (haptic coupling) and seeing their fellow dancers (visual coupling). Analyses of group synchrony using cluster phase analysis demonstrated that selective elimination of any one of the three types of sensory coupling significantly reduced group synchrony, where haptic coupling had the strongest effect on movements in the horizontal plane, but also impacted the vertical axis. This study provides some of the first evidence of how sensory couplings support multi-person coordination in a large group, and in particular the effect of body contact on this coordination.

1. Introduction

Group dancing has been a fundamental part of human behavior for most of recorded history (Sachs, 1937). From the tribal dances of our ancient ancestors to the dance battles and flash mobs of modern society, group dancing is an expression of solidarity and collective emotion (Hanna, 1979). Indeed, to dance with others is to connect with them in both body and mind, forming a single system of sensorimotor activity – collectively entrained via physical (haptic), visual, and auditory information – that moves together in time (McNeil, 1995). One could even argue that synchronized group dancing is the closest that human groups ever come to achieving the properties of an "organism" (Sober & Wilson, 1998). From an evolutionary standpoint, there is now mounting evidence that synchronizing rhythmically with others can enhance feelings of altruism and cooperation (Cirelli, 2018; Launay, Tarr, & Dunbar, 2016; Reddish, Fischer, & Bulbulia, 2013), an important requirement for groups to flourish. Moreover, group dances generally assume the form of specific spatial configurations, often having symbolic meanings. For example, the universal dance configuration of a circle symbolizes not only unity and equality but also a sense of encircling something (Sachs, 1937).

Despite the historical importance and ubiquitous presence of group dancing across cultures and throughout history, very little research has explored the underlying sensorimotor mechanisms that support it. Group dancing is a fascinating and understudied model of joint action in which dancers achieve a sense of group synchronization by relying on three simultaneous sources of sensory

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* Corresponding author.
E-mail address: stebro@mcmaster.ca (S. Brown).

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information: 1) all dancers entrain their movements to the beat of music (external auditory coupling), 2) they see one another performing identical movement patterns (mutual visual coupling), and 3) they have physical contact with their adjacent partners through hand hold (mutual haptic coupling). Because the paradigm of previous work on joint action has been to examine coordination in dyads, group dancing affords the opportunity to look at coordination at the level of larger groups. In addition, while work in the area of dyadic coordination has primarily focused on the role of visual and auditory couplings (Desmet, Leman, Lesaffre, & Bruyn, 2010; Nessler & Gilliland, 2009; Nowicki, Prinz, Grosjean, Repp, & Keller, 2013; Richardson, Lopresti-Goodman, Mancini, Kay, & Schmidt, 2008; Richardson, Marsh, & Schmidt, 2005; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007), far less work has looked at haptic coupling (Nessler & Gilliland, 2009; Sofianidis & Hatzitaki, 2015; Sofianidis, Hatzitaki, Grouios, Johannsen, & Wing, 2012; van der Wel, Knoblich, & Sebanz, 2011; Zivotofsky & Hausdorff, 2007), which is a key feature of many forms of group dancing, from couple dances through to circle dances involving hundreds of people. This research has shown that all sensory couplings make a contribution to the stability of interpersonal coordination, although to varying degrees. The relative influence of the visual and auditory modalities on coordination seems to depend on context (Desmet et al., 2010; Nessler & Gilliland, 2009; Nowicki et al., 2013; Richardson et al., 2005, 2007, 2008). In addition, studies have shown that haptic coupling between individuals stabilizes interpersonal coordination more efficiently than does either visual or auditory information exchange (Nessler & Gilliland, 2009; Sofianidis & Hatzitaki, 2015; Sofianidis et al., 2012; Zivotofsky & Hausdorff, 2007).

A significant limitation of much of this research is that it focuses either on unintentional coordination or on simple non-natural movements or tapping tasks, whereas group dancing (and group musical performance as well) is predicated on the joint goal of achieving *group synchrony* (Keller, Novembre, & Hove, 2014; Knoblich & Sebanz, 2008; Phillips-Silver, Aktipis, & Bryant, 2010; Reddish et al., 2013; Sacheli, Aglioti, & Candidi, 2015). The aim of the current study was to explore how group synchrony (i.e., the stability of group sensorimotor coordination) is influenced by the auditory, visual, and haptic streams of informational coupling that come together in group dance performance. The study also examined how the impact of these information sources was dependent on the spatial distribution of members across the group. For example, when dancing in a closed circle, a given dancer often has reduced visual awareness of the dancers on either side of her/him, but the strongest haptic contact with those dancers (i.e., due to physical contact through hand hold). We explored this issue by examining not only synchrony in the group as a whole, but by analyzing "trios" of dancers comprised of a given dancer and the individual dancers on each side of her/him. We did this across all possible trio groupings in the circle, with the aim of exploring whether coupling with one's immediate neighbors is stronger than coupling with dancers further away or with the group overall, as well as whether the effect of neighbor distance varies depending on the availability of different streams of sensory coupling.

In order to examine how collective synchronization emerges during group dancing, we investigated for the first time the coordination dynamics of a group of 13 expert folk dancers performing in a circle. The dancers' full-body movements were recorded using 3D motion capture while the availability of either auditory, visual, or haptic coupling was manipulated. We analyzed the synchronization of the dancers' body movements across the different conditions using a measure of global group synchrony (Richardson, Garcia, Frank, Gergor, & Marsh, 2012), rather than looking at averaged comparisons based on pairs of dancers. The overall aim was to explore the degree to which the different sensory couplings influence the stability of group dance behavior, as well as the degree to which the overall stability of this behavior varies as a function of local (neighbor) interactions. Based on the literature reviewed above on dyadic entrainment, we predicted that haptic coupling would have a stronger impact on group synchrony than either auditory or visual couplings. We also predicted that dancers would be more synchronized with their immediate neighbors than with more-distant dancers.

2. Methods

2.1. Participants

Fourteen folk dancers (11 females, 69.3 ± 5.9 years old) participated in the study after giving their informed consent, in accordance with the guidelines of the local ethics board (McMaster Research Ethics Board, protocol #2014 235). All dancers were recruited from a local recreational folk dancing club, where they had been dancing 14.6 ± 7.4 h per month for the past 32.3 ± 14.4 years. Six of the dancers had other forms of dance experience (ballet, contemporary, Scottish, English country). All dancers had normal hearing and musculoskeletal abilities, as well as normal or corrected-to-normal vision. They received monetary compensation for their participation.

2.2. Stimuli

Two Greek folk dances were performed in a closed circle to recorded musical excerpts: *Syrtos Pyleas* (Dance 1) and *Kritikos Syrtos* (Dance 2). Both dances were well known to the dancers. They were chosen because they represented different levels of complexity, where the pattern of steps for *Syrtos Pyleas* is simpler than that for *Kritikos Syrtos*. Each dance contained a basic sequence of 12 steps that was repeated throughout the dance, having a duration of 6–7 s. The musical stimuli used in the experiment permitted six repetitions of the sequence for each dance (i.e., 72 steps in total), making each trial 35–45 s in duration. Table 1 contains information about the characteristics of the dances and their associated musical excerpts. Fig. S1 presents a simplified score of the musical excerpts, a verbal description of the dance steps, and a graphic mapping of those steps onto the musical beats in the score.

Table 1
Characteristics of the dances and their music.

		Dance 1: Syrtos Pyleas	**Dance 2: Kritikos Syrtos**
	Excerpt duration	44s	56s
	Dance sequence fits musical phrase	Yes	No
Dance characteristics	Sequence duration	5.73s	7.29s
	Number of steps per sequence	12	12
	Complexity	Medium	Difficult
Music characteristics	Meter	7/8	4/4
	Tempo	126 bpm	132 bpm

2.3. Procedure

Thirteen of the dancers formed a closed circle by holding hands, while the leader (the dance group's teacher) danced in the center of the circle. Together they performed the dances under four conditions. In the control condition, they danced as usual with all sensory information present: to music (auditory), while holding hands (haptic), and with the eyes open (visual). This setting is schematized in Fig. 1A. In each of the three other conditions, one sensory modality was selectively inhibited: 1) in the noTouch condition, the participants danced without holding hands; 2) in the noVision condition, they danced with their eyes closed; and 3) in the noMusic condition, they danced without music. Because the leader was inside the circle, she was not in physical contact with any of the dancers. In addition, her eyes were open during all conditions, including the noVision condition. Finally, she wore wireless headphones (Silent Disco King) during the noMusic condition so as to permit her, but not the other dancers, to hear the music.

For each dance, the dancers performed each of the four conditions five times, resulting in 20 trials per dance. The dances and conditions were performed in a counterbalanced order. A break was taken halfway through the session. The entire experiment lasted 3 h, including the set-up time. After the experiment, the participants filled out a questionnaire about their dance experience, and reported (on a 5-point scale) their familiarity with the dances, competency at the dances, the perceived difficulty of each condition, and the enjoyability of each condition.

2.4. Apparatus

The experiment took place on the stage of a large black-box performance laboratory. Each dancer was fitted with 10 passive motion-capture markers placed on the right and left foot tips, heels, knees, and waist (iliac crest), with single markers placed on the neck (vertebral level C7) and the left hand. The 3-dimensional coordinates of the markers were recorded at 120 Hz using a 23-camera optical motion capture system (Qualisys). The musical stimuli were presented using a speaker (Dynaudio Accoustics BM6A) located approximately 5 m from the dancers. To synchronize the music with the motion-capture system, triggers in the audio signal were converted into TTL (transistor-transistor logic) pulses with an Arduino Uno microcontroller and then plugged into the Qualisys Track Manager system.

Fig. 1. Organization of the sensory couplings between the dancers, the group's leader, and the music. (A) The dancers (in grey) formed a circle, with a leader (in black) in the middle. The handholding between each dancer and his/her two neighbors formed a bidirectional haptic coupling (purple arrow and handhold icon). The dancers could see one another and the group's leader via semi-bidirectional visual coupling (red arrow and eye icon). Finally, the dancers could hear the music via unidirectional auditory coupling (green arrow and musical-note icon). (B) Scheme of the local axis system centered on each dancer, where the x-axis represents the medio-lateral body axis, the y-axis represents the antero-posterior body axis, and the z-axis represents the vertical axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.5. Conversion to local coordinates

Three-dimensional coordinates were converted to local coordinates centered on each dancer (Fig. 1B). The two waist markers were used to define the orientation of the local x-axis. The z-axis (vertical) was not changed. The local y-axis was defined orthogonally to the x- and z-axes. Finally, the local origin was defined as the mid-point between the right and left waist markers, projected onto floor (the $z = 0$ plane). The three axes were defined for each dancer in the following manner: the x-axis corresponds to the *medio-lateral* body axis, with positive values indicating motion in the rightward direction; the y-axis corresponds to the *antero-posterior* body axis, with positive values indicating motion in the forward direction; and the z-axis corresponds to the *infero-superior* axis, with positive values indicating motion in the upward direction.

Missing data were filled in using a two-step process (see Supplementary material for details). One dancer was excluded from the analysis of both dances due to a significant amount of data missing from the dancer's waist markers (preventing conversion to the local system), and another dancer was excluded from the analysis of Dance 2 for the same reason.

2.6. Analyses

Analyses were performed in the x, y, and z local trajectories of the foot markers, encompassing the right and left foot tips and heels (4 markers). After preprocessing the time-series (see Supplementary material for details), we calculated the group synchronization and the degree of synchronization of each dancer to the group using cluster phase analysis (Frank & Richardson, 2010; Richardson et al., 2012; see Supplementary material for more details). This was done for each dance, axis, condition, marker, and trial for the 12 dancers in Dance 1 and the 11 dancers in Dance 2. Group and individual synchrony values can range between 0 and 1, where 0 indicates a total absence of synchrony and 1 indicates perfect synchrony. We used Pearson correlations to examine the relation between the synchronization of each dancer to the group and their self-reported values of dance experience, familiarity with the dances, and ease at dancing in each condition. The significance level was set to $p \leq 0.016$ (i.e., $p = 0.05/3$) to correct for the three axes examined.

The synchronization of individuals with the group was further explored in order to identify outliers. A dancer was considered an outlier if s/he was poorly synchronized with the group over all conditions (i.e., where synchrony values were close to 0) or if s/he was significantly worse in one subset of the conditions, in general by being more than 2 standard deviations from the mean. It was found that dancers had difficulty performing Dance 2 with the eyes closed because the phrase structure of the dance does not map well onto the phrase structure of the music. In addition, this dance does not have a clear change of direction. Therefore, if one misses even a single step, it is difficult to use the music or haptic information to catch up. As can be seen in Fig. 2, P9 was more than 4 standard deviations from the mean for both dances, and was thus excluded from the analysis of both dances. P4 for Dance 2 was likewise excluded for being more than 4 standard deviations from the mean. P8 for Dance 2 was only 1.5 standard deviations from the mean. However, our reason for excluding this participant from the analysis of Dance 2 is that this person, like the other three outliers, showed a total interruption of dancing during some noVision trials, whereas none of the non-outlier participants ever showed complete interruptions. Hence, excluding P8 for Dance 2 ensured that the comparison between sensory-coupling mechanisms only included trials in which all participants performed the dances without any interruptions. Identical outliers were identified using Procrustes analysis (Goodall, 1991; see Fig. S2 and Supplementary material for details). As a result of the exclusions, the cluster phase analysis was rerun without the outliers, which resulted in 11 dancers for Dance 1 and 8 dancers for Dance 2.

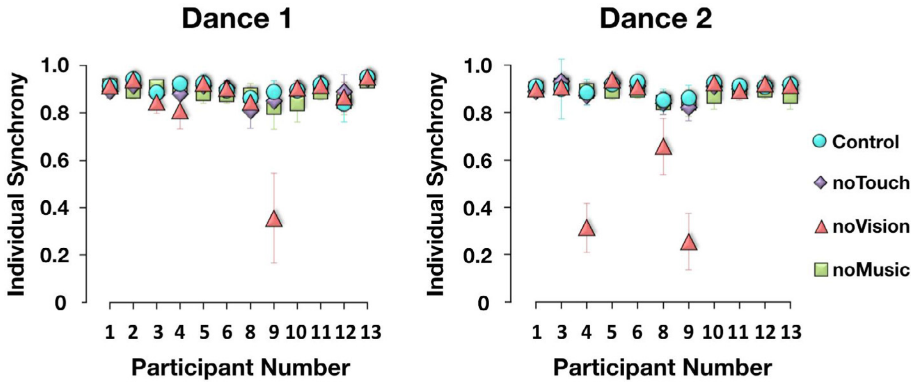

Fig. 2. Cluster phase analysis of the synchronization of each dancer with the group. Most dancers were highly synchronized with the group in all conditions in both dances. However, in Dance 1, participant 9 was not synchronized with the group when dancing with the eyes closed. In Dance 2, participants 4, 8 and 9 were not synchronized with the group when dancing with the eyes closed. These participants were considered as outliers and were removed from the analyses. Note that participant 7 in both dances and participant 2 in Dance 2 are absent due to excessive missing data. Error bars indicate the standard deviation.

2.7. Statististics and model reduction

To assess whether the overall effects were similar in the two dances and to avoid overly complex models, we first tested, for each analysis, if the dances interacted with the main factor(s) of interest, hereafter referred to as the “pre-analysis” (see Supplementary materials for details). If they did, then we performed the analysis on each dance separately. Otherwise, we performed the analyses across both dances, without testing the interaction between dances and other factors. To examine effects on global group synchrony, we created linear models of the experimental factors in R (R Core Team, 2014). Since we had only one observation per cell, no interactions were modeled with the repeated factors (sequences, trials). Analyses of variance (ANOVAs) were computed from the linear fits of the linear models. To test effects on local synchrony (trios), we performed linear mixed models using the LME4 package in R (Bates, Maechler, Bolker, & Walker, 2015), and repeated-measures ANOVAs were computed from these models. Effect sizes were computed using the SJSTATS package in R (Lüdecke, 2017). Since our goal was to look at group synchrony, we had only one group in the analysis. However, we also performed a similar but more standard analysis using the synchronization values of each individual dancer (the methods and results can be found in the Supplementary materials). There was no difference in results between the two analyses.

2.7.1. Group synchrony

The group synchrony values were averaged within each sequence. We first tested for a potential interaction between axes and the four experimental conditions (see Supplementary material for details). There was a significant interaction between conditions and axes (Table S2). This result was due to the z axis, since the interaction between conditions and axes was not significant in a model without the z axis (i.e., xy), but was significant when including the z axis (i.e., xz and yz, see Table S2). Therefore, in all of following analyses, we tested for effects using two separate models: one for the x and y axes on one side, and one for the z axis on the other side. Additionally, the pre-analysis showed no interaction with dances (Table S2), and so both dances were combined in each model. We ran two ANOVAs looking at the 4 conditions (control, noTouch, noVision, noMusic) × 2 markers (foot tip, heel) × 2 sides (left, right). The two dances and the 30 sequences per dance (6 repetitions × 5 trials) were entered into the models as factors of no interest (interactions were not tested), as were the two axes of the xy model. The significance level of the ANOVAs was set to $p < 0.025$ to correct for the two models ($p = 0.05/2$), where significant effects were explored using Bonferroni-corrected post-hoc analyses. We also ran ANOVAs to test the effect of sequence repetition over the course of the musical excerpt for each dance separately, using two 6 repetitions × 4 conditions (control, noTouch, noVision, noMusic) × 3 axes (x, y, z) analyses. The 5 trials and 4 markers were entered into the model as factors of no interest (interactions were not tested). The significance level of the ANOVAs was set to $p < 0.025$ to correct for the two models ($p = 0.05/2$), where the significant effects were explored using Bonferroni-corrected post-hoc analyses.

2.7.2. Synchronization within neighbor trios

Beyond looking at global effects at the whole-group level, we wanted to examine if dancers were more synchronized with their adjacent neighbors than with dancers further along the circle. To do this, we developed the concept of a “trio”, referring to a given dancer and the individual dancers to her/his right and left, respectively. We measured the synchrony of each dancer with their two neighbors as a function of the neighbor’s distance from the central dancer (graphically displayed in Fig. 5A in the Section 3), where a distance of “1p” refers to those two people directly neighboring the dancer to the right and left (where “p” stands for person), a distance of “2p” refers to those dancers two positions out along the circle from the central dancer, up to a distance of “4p” on either side of the central dancer, which created the maximum trio distancing in our circle of 13 dancers. Because this analysis investigated the position of dancers along the circle, we included outliers here, although we excluded the noVision condition, where the outliers performed poorly and experienced interruptions in their dancing.

The group-synchrony values for each trio were averaged within each trial. The pre-analysis showed that the effect of neighbor distance on conditions was identical for both dances (see Supplementary materials), and so both dances were included in both the xy and z models. We tested the influence of neighbor distance on group synchrony with a 4 neighbor-distances (1p, 2p, 3p, 4p) × 4 conditions (control, noTouch, noVision, noMusic) × 2 markers (foot tip, heel) × 2 sides (left, right) repeated-measures ANOVAs on the linear mixed models to account for trio members. The two dances and the five trials were entered into the models as factors of no interest (interactions were not tested), as were the two axes of the xy model. The significance level of the ANOVAs was set to $p < 0.025$ to correct for the two models ($p = 0.05/2$), where significant effects were explored using Bonferroni-corrected post-hoc analyses.

3. Results

3.1. Correlation analysis

For both dances and all three axes of motion, the synchronization level of each dancer to the group as a whole correlated significantly with a dancer’s prior familiarity with the dance, with Pearson r values ranging from 0.35 to 0.54 (Table 2). Individual-level synchrony values were also significantly correlated with the perceived ease (difficulty) at performing the dance in each condition for Dance 2, but not for Dance 1. Finally, no correlation was found between synchrony and overall experience at dancing.

Table 2

Correlations between the synchronization of each dancer to the group and self-reported values of: familiarity of a dancer with each dance used in the experiment, difficulty of the four conditions (for each dance), and overall folk dancing experience. Significant effects ($p < 0.16$) are in bold.

		Dance 1			Dance 2		
		Medio-lateral	Antero-posterior	Vertical	Medio-lateral	Antero-posterior	Vertical
Dance familiarity	Pearson's r	**0.381**	**0.400**	**0.353**	**0.540**	**0.442**	**0.440**
	p-value	**0.008**	**0.005**	**0.014**	**< 0.001**	**0.003**	**0.003**
Condition difficulty	Pearson's r	0.289	0.015	0.299	**0.560**	**0.620**	**0.590**
	p-value	0.046	0.920	0.039	**< 0.001**	**< 0.001**	**< 0.001**
Folk dance experience	Pearson's r	0.217	−0.259	0.167	0.129	0.153	0.174
	p-value	0.138	0.076	0.256	0.404	0.322	0.259

3.2. Cluster phase analysis: effect of sensory couplings on synchronization

The mean group synchrony value was overall high for both dances (Dance 1: 0.89 ± 0.05, Dance 2: 0.93 ± 0.04, where a value of 1 is the maximum synchrony), highlighting the clear expertise of this cohort of folk dancers at performing these dances. The effect of eliminating a single sensory coupling was significant for both the combined horizontal axes [$F(3,1803) = 24.53$, $p < 0.001$, η^2 part. = 0.039] and the vertical axis [$F(3,879) = 21.79$, $p < 0.001$, η^2 part. = 0.069]. The results are shown graphically in Fig. 3, where the x and y components of the horizontal axis are plotted separately. For group synchrony in the horizontal axes, the noTouch, noVision, and noMusic conditions all resulted in a significant decrease in group synchrony compared to the control condition. The lowest level of synchrony was observed when the dancers were not able to hold hands, where group synchrony for the noTouch condition was significantly lower than that for the noVision, noMusic, and control conditions. There was no difference between the noMusic and noVision conditions for the horizontal axes. For the vertical axis, by contrast, only the noMusic and noTouch conditions resulted in a significant decrease in group synchrony compared to the control condition; there was no difference between the noVision and control conditions. The lowest level of synchrony was observed when the dancers could not hear the music, where group synchrony for the noMusic condition was significantly lower than that for the noTouch, noVision, and control conditions.

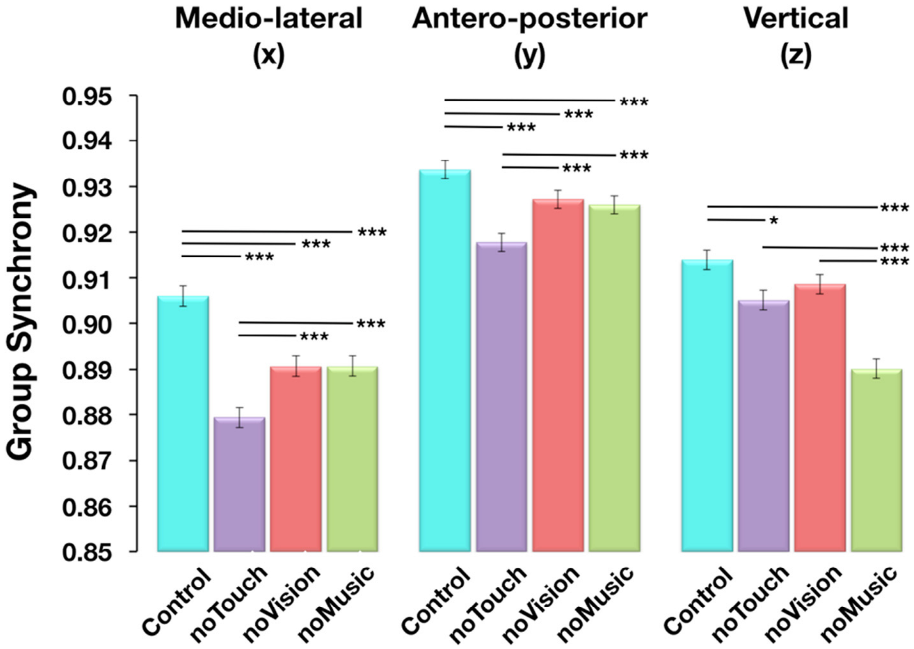

Fig. 3. Group synchrony in the medio-lateral (x), antero-posterior (y), and vertical (z) axes for each condition. In the control condition, the dancers shared three types of coupling: haptic (holding the neighbors' hands), visual (seeing the other dancers and the leader), and auditory (hearing the music). In the three other conditions, one of these cues was selectively eliminated. The medio-lateral and antero-posterior axes (spatio-temporal dimension: "where to step") show an effect of all sensory couplings on group synchrony, most significantly for touch. The vertical axis (temporal dimension only: "when to step") shows an effect of all couplings, except for vision, and most significantly for music. Note that the medio-lateral and antero-posterior axes were tested in the same model, such that the post-hoc analysis reflects the difference between conditions on the mean of both axes. This was possible because there was no interaction between condition and axis in this model. $^{***}p < 0.001$, $^{**}p < 0.01$. $^{*}p < 0.05$. The results represent the means for both dances. Error bars indicate standard errors of the mean.

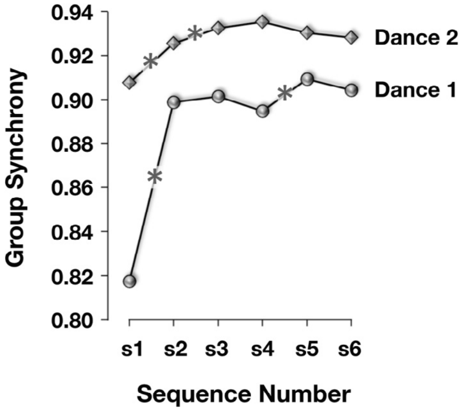

Fig. 4. Emergence of group synchrony in each repeated sequence over the course of the music. In both dances, the group synchrony increased with sequence repetition. $^*p < 0.05$ between consecutive sequences. Error bars indicate standard errors of the mean.

Overall, we observed a dissociation between the horizontal axes – where haptic interaction had the strongest effect on synchrony – and the vertical axis, where music had the strongest effect, and visual coupling had no effect.

There was no interaction between condition and marker and/or side, except between condition and side for the horizontal axes [F (3,1803) = 5.70, $p < 0.001$, η^2 part. = 0.009], where there was significantly less coordination for the right side for the noTouch condition. For both dances, the dancers progressed in the rightward direction, and it seems that the absence of physical contact with neighbors had the strongest effect on the leading (right) foot.

3.3. Cluster phase analysis: effect of sequence repetition

During each trial, the dancers repeated the sequence of steps six times over the course of the musical excerpt. As shown in Fig. 4, there was a significant effect of sequence repetition on group synchrony for both dances [Dance 1: [F(5,1060) = 446.87, $p < 0.001$, η^2 part. = 0.678; Dance 2: F(5,991) = 50.59, $p < 0.001$, η^2 part. = 0.203], such that group synchrony increased over the course of the musical excerpt. The dancers were the least synchronized in the first sequence and reached maximum synchrony by the the fifth sequence in Dance 1 and the third sequence in Dance 2.

3.4. Synchronization with the dancers' neighbors

We next examined synchrony with the dancers' neighbors. For this, we looked at "trios" of dancers (i.e., a given dancer plus the individual dancers on each side of that person), and analyzed the synchronization of trios as a function of distance from the neighbors, while including outliers to preserve the continuity of the chain, but excluding the difficult noVision condition (Fig. 5A). There was a main effect of neighbor distance on both axes [horizontal: F(3,8234) = 19.07, $p < 0.001$, η^2 part. = 0.968; vertical: F (3,4111) = 36.57, $p < 0.001$, η^2 part. = 0.995], but no interaction between distance and conditions, and no interaction between distance, condition, marker, and/or side in all axes (Fig. 5B). The synchronization with neighbors decreased gradually with increasing distance (from 1p to 3p, with no difference between 3p and 4p), doing so similarly across all conditions.

4. Discussion

As group dancing is a paradigmatic example of the rhythmic, coordinated, and cooperative behaviors that humans engage in, we examined how multisensory interactions affected the coordination dynamics of a group of 13 expert folk dancers performing two familiar Greek dances to music while holding hands in a circle, with the group's leader dancing in the center. The dancers synchronized simultaneously with their neighbors (haptic and visual couplings), the group's leader (visual coupling), and the recorded music (auditory coupling). Using cluster phase analysis to measure group synchrony, we examined how the dancers synchronized overall, and how this synchrony was altered when any one of the sensory couplings was unavailable to the dancers. Similar results were obtained for both of the dances, indicating that the results were not dependent on any one specific rhythmic pattern or pattern of steps. Globally, we found that couplings with auditory, visual, and haptic information all contributed to group synchrony. Haptic coupling had the the largest effect on the horizontal plane, while musical coupling had the largest effect on the vertical axis, although haptic coupling made a significant contribution to the vertical axis as well.

4.1. Relative influence of sensory couplings on group synchrony

The absence of haptic coupling between the dancers reduced group synchrony in all three axes, and did so more strongly than vision and audition in all but the vertical axis. The results of the current experiment suggest that haptic coupling has its principal

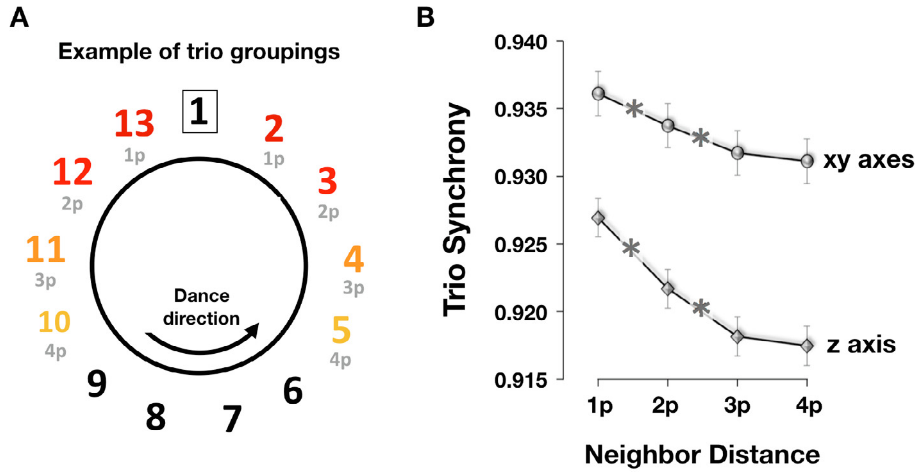

Fig. 5. Synchronization in trios of dancers. (A) Scheme for the circle of 13 dancers. Trios are established based on a central dancer (trio center; dancer 1 in this example) and the individual dancers to his/her right and left, respectively. Neighbor distance is measured as the distance in number of participants (from 1 to 4) between a central dancer and his/her neighbors. For example, dancers 13 and 2 are at a distance of one participant (1p) from dancer 1, while dancers 12 and 3 are at a distance of 2p from dancer 1, and so on. (B) Synchrony with neighbors as a function of neighbor distance, showing that synchrony decreases significantly with increasing neighbor distance for both the horizontal and vertical axes. $^{*}p < 0.05$ between consecutive sequences. The results represent the means for both dances and all three included conditions (noVision was excluded). Error bars indicate standard errors of the mean.

effect on movements in the horizontal plane, while also having a significant effect on the vertical axis. This is consistent with intuitions about the nature of dancing in a closed circle, since most of the pushing and pulling forces that occur with handhold act on the movements of dancers in the horizontal plane via side-to-side and forward-backward forces. These results with a large group are also consistent with several studies of dyadic synchronization, where spontaneous mutual entrainment is stronger when two individuals are haptically coupled than when they are only coupled visually or acoustically (Nessler & Gilliland, 2009; Sofianidis & Hatzitaki, 2015; Sofianidis et al., 2012; Zivotofsky & Hausdorff, 2007). When people are haptically coupled, the movement of one individual is directly perceived by partners as a pushing or pulling force, and so the partners can smoothly coordinate their movements with one another (van der Wel et al., 2011). Haptic contact supports both informational (sensory) and mechanical (physical) coupling, resulting in a higher coupling strength than visual or auditory coupling (Harrison & Richardson, 2009; Richardson et al., 2008). It has been suggested that haptic coupling between two individuals allows strong mutual entrainment even when the mechanical contribution is minimized, such as during light interpersonal touch (Sofianidis & Hatzitaki, 2015). However, it was not possible in our study to separate the contribution of purely tactile contact from mechanical sources in haptic coupling. We can assume that the interpersonal mechanical coupling during handholding is important. This may explain why group synchrony was most strongly reduced in the absence of haptic coupling between dancers.

4.2. Relative influence of sensory couplings on movement axes

Group synchrony was found to be high for all three body axes, most likely due to the dancers' strong familiarity with the dances and to the fact that the dancers shared an explicit common goal (Ellamil, Berson, Wong, Buckley, & Margulies, 2016; Keller et al., 2014; Sacheli et al., 2015). However, we also found evidence that different sensory couplings supported different aspects of group synchronization. When looking at the influence of visual and auditory couplings on group synchrony, we found an interaction with body axes. The medio-lateral and antero-posterior axes together form the horizontal plane in which the dancers performed their steps, and the trajectory of the feet in the horizontal plane (see Fig. S2B) contains spatio-temporal information for the movements, namely *where* or *how* to step. By contrast, the trajectory of the feet in the vertical axis mainly contains temporal information of the movement, namely *when* to step and make contact with the floor. We found that the absence of haptic coupling between dancers affected group synchronization in both axes, but that the absence of either of the other two couplings preferentially affected only one axis. The absence of visual coupling between dancers, and between the dancers and the leader, affected group synchronization in the horizontal axes, but not the vertical axis. Conversely, the auditory coupling of the dancers to the music influenced group synchrony on all axes, but much more strongly in the vertical axis than the horizontal axes. This is consistent with literature showing that an individual synchronizes more accurately to discrete (temporally-precise) auditory stimuli, but to continuous (spatially-moving) visual stimuli (Hove, Fairhurst, Kotz, & Keller, 2013; Hove, Iversen, Zhang, & Repp, 2013; Iversen, Patel, Nicodemus, & Emmorey, 2015). Sensorimotor synchronization is improved when the stimuli match the perception of the movement in a given modality (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Hove, Fairhurst, et al., 2013). Therefore, the vertical trajectory of the feet (up and down) is more likely to be synchronized to the discreteness of the musical beats (auditory coupling), whereas the spatial trajectory of the feet is more likely to match the shape of the leader's foot trajectory (visual coupling). Our study shows that the synchronization mechanisms observed in a complex and ecologically realistic context like group dancing match well to those observed using inanimate stimuli in laboratory-controlled settings.

4.3. Influence of neighbors

We observed that the dancers were more synchronized with their immediate neighbors than with distant neighbors, regardless of the condition. The further that dancers were from a given reference dancer, the less synchronized they were with one another. This effect is likely due to haptic and/or visual coupling, as all dancers heard the same music, but they were in direct contact only with their two immediate neighbors, and could not see all dancers equally well. In a similar vein, Honisch, Elliott, Jacoby, and Wing (2016) found a cumulative effect of timekeeper variance when participants in a chain had to visually synchronize to their preceding neighbor. We presume that the decreased synchrony observed with increasing neighbor distance was due to an accumulation of synchronization-variance from one dancer to the next. Since our chain was a closed circle, this accumulation of variance had to be balanced overall, much like the pressure of an incompressible fluid in a pliable container, or like self-organized, complex dissipative systems more generally (Kelso, 1995; Kugler & Turvey, 2015).

4.4. Limitations

Three caveats need to be mentioned with respect to our experimental setting and the manipulation of visual and auditory couplings. First, the visual coupling between dancers was prevented by asking the participants to close their eyes while performing the dances, which may have disrupted their balance and, in turn, their ability to synchronize. However, we did not observe a drastic loss of group synchrony in this condition, and none at all in the vertical axis. We therefore assume that dancers did not experience a loss of balance in the noVision condition. Second, we eliminated auditory coupling by preventing the dancers from hearing the music, but not each other's steps. While we can assume that the dancers could barely hear their steps when the music was playing, it is possible that group synchrony would have been even more decreased in the absence of music if all sources of auditory coupling were successfully masked. Further studies are necessary to disentangle the impact of these two sources of auditory coupling on group synchrony, one being external to the group of dancers (the recorded music) and the other emerging from their intrinsic movement patterns. Third, the group synchrony was quite high for this cohort of participants, no doubt reflecting their extensive experience as dancers and their prior familiarity with these specific dances. Future studies should examine less-experienced dancers so as to work with a lower baseline of group synchrony than that which occurred in the present study. This could be carried out as a training study in novices, in which group synchrony increases with increased training and experience.

4.5. 4.5. Conclusions

The present study is the first one to examine the multisensory couplings underlying group coordination using a cohort of individuals specialized in group synchronization with physical contact. The capacity of humans to coordinate actions with one another and with the environment makes possible the infinite diversity that is observed in coordinated group behaviors, such as conversation, group musical performance, and the playing of team sports. This variety is mediated by dynamic coordination of the component parts. This requires people to continuously respond and adapt to one another based on information available from the environment and the actions of others. We demonstrated here that individuals engaged in group dancing relied most strongly on haptic information to synchronize with the group, and that the reliance on the visual and auditory information depended on the spatiotemporal context. This study furthers our understanding of the dynamics of multi-person and multisensory coordination in an ecological and culturally-meaningful context.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2018.12.005.

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