RECURRENCE ANALYSIS OF INTERPERSONAL SYNCHRONIZATION IN CHILDREN DURING TAP SIDE OF AEROBICS

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Research indicates that during some interpersonal interactions– including for example side-by-side walking (Nessler & Gilliland, 2009)– people may spontaneously synchronize the rhythm of their movements to those of another person, especially if one has the opportunity to visually perceive the behavior of the second person (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). Additionally, during rhythmical behavior, research has indicated that people can establish two relatively stable patterns of coordination: (i) inphase - where homologous muscle groups contract simultaneously; and, (ii) antiphase - where homologous muscle groups contract in an alternating fashion. When neither of these patterns is occurring, the actor is said to be in transition where they might be involuntarily moving towards a stable pattern, or synchronization is simply not being established (Kelso, 1995). With regards to rhythmic limb coordination, inphase synchronization is considered the most natural and easy mode of coordination to maintain and there is a tendency for subjects to switch spontaneously from antiphase to inphase state (Amazeen, Schmidt, & Turvey, 1995; Kelso, 1995; Schmidt & Lee, 2011).

Previous investigations have employed recurrence quantification analysis to analyze the attractor strength of interpersonal limb coordination (Richardson et al., 2008). Recurrence analysis (RQA) is a nonlinear and multi-dimensional technique involves the reconstruction of a phase space. Points that are separated in time but spatial neighbors in the reconstructed space reflect recurrence in time— as time progresses data points return, or *recur*, to the same region of phase space. Recurrent points may be defined by denoting a sphere of radius r centered on a point $x(i)$ in the reconstructed space and to count the number of points which are within the distance r. If this distance is less than or equal to radius, then the points are considered to be recurrent (Riley, Balasubramaniam, & Turvey, 1999). These points may be graphically represented on an $N \times N$ matrix (where N is the length of the time series) called a *recurrence plot*. RQA, a quantitative analysis of this plot, has been shown to be a useful tool in the study of dynamic systems (Webber & Zbilut, 2005). The cross recurrence (CRQA) is a bivariate extension of the recurrence analysis and was introduced to analyze the dependencies between two different systems by comparing their states (Marwan, Romano, Thiel, & Kurths, 2007). CRQA has several output measures to describe the system under observation: *%REC* is the rate of recurrence, a measure of the percentage of recurrent points of all possible points on the recurrence plot; *%DET* is the percentage of recurrent points which form diagonal line segments, these lines indicate that the system is revisiting the same region of the attractor, so *%DET* reflects the degree of determinism in the system; Meanline in is the mean length of diagonal line segments. A longer Meanline implies that the system on average enters longer deterministic states, and as such is interpreted here as a measure of periodicity. *Maxline* is the length of the longest diagonal line segment, and is a measure of the overall stability of the system; *Entropy* is a measure of the complexity of the deterministic structure of the time series; higher entropy reflects a more complex system; finally, Relative entropy, a measure that reduces the influence of the number of different line lengths used in the calculation of entropy, is a measure of the statistical difference (divergence) between two distributions (an index of phase space divergence of the deterministic structure in the system) (Riley et al., 1999; Webber & Zbilut, 2005).

Previous investigations comparing the attractor strength of interpersonal interlimb coordination using cross-recurrence analysis have indicated that inphase coordination has a stronger attractor than antiphase coordination (Richardson, Lopresti-Goodman, Mancini, Kay, & Schmidt, 2008). This finding is consistent with behavioral data noting that the pattern of inphase coordination is more stable and easy to maintain than antiphase— suggesting that the system is more attracted to stay or to switch to inphase state.

With this in mind, the purpose of the present investigation was to demonstrate that CRQA might be used as a reliable metric to detect periodicity and determinism during interpersonal unintentional synchronization in children. Pairs of children performed tap side, a specific step of aerobics which consists of a two-time movement of adduction and abduction of one leg relative to the other leg that is static. If interpersonal synchronization between two children is observed, then it will be more likely (attracted) for patterns of inphase coordination to occur, and that these patterns of coordination should exhibit a more deterministic structure than moments of antiphase coordination or transitions between inphase and antiphase.

Method

The sample was composed of 12 children: 5 boys and 7 girls; mean age: 4.83 ± 0.83 years-old. The children's assent and the informed consent of their parent or guardian was obtained.

Two sessions of data collection were conducted, each lasting one-minute in duration. The first testing session comprised of individual participants. Data from this initial session was later used to assign the dyad pairs. The dyads were formed on the basis of individual natural velocity of tap side aerobic coordination and composed of a slow and a fast child, with similar leg lengths (Nessler & Gilliland, 2009). The second testing session comprised of dyad pairs;

participants were required to look at the other person in their pair during the execution of tap side. No other information (e.g., about rhythm of execution, or technical correction) was provided to the participants. The children performed the task at their natural speed.

Kinematic analysis was made with the program Ariel Performance Analysis System (APAS, version 2003) with the digital filter "Direct Linear Transformation" set to a cutoff of 5 Hz (for smoothing of the data). The angles of the lower limb knee position that performed the tap side were derived using APAS software. Time series of changes in participants' knee angle were constructed for each dyad, and were divided in episodes by means of visual inspection. An episode was defined as two or more consecutive cycles of tap side where the dyad's leg movements were either inphase (both participants' limbs oscillated in identical parts of the cycle at the same time), *antiphase* (both participants' limbs oscillated in opposite parts of the cycle at the same time) or in a period of *transition* (see Figure 1). Transitions marked periods of time where the dyads movement changed from one mode of synchrony to another, or were defined as periods where the phase lag between limb movements was longer than 200 ms. The longest episode of each type was analyzed using cross recurrence quantification analysis techniques.

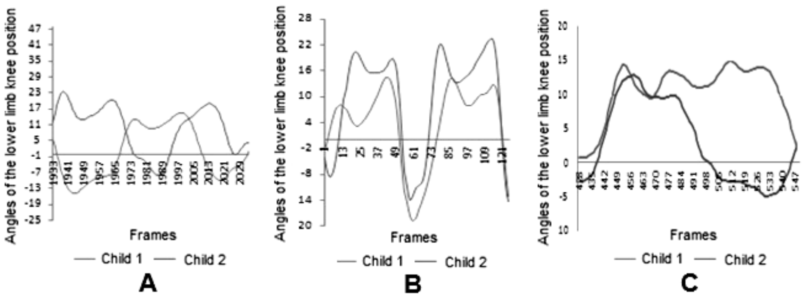

Figure 1. Examples time series graphs of antiphase, inphase and transition episodes.

Both time series were reconstructed in phase space in the following manner: time delay was detected visually in the first minimum of autocorrelation or mutual information (AMI) graphic; the number of embedding dimensions was detected visually in false nearest neighbors (FNN) graphic, with the criterion of percentage of FNN when it is closest to zero (Zbilut, Thomasson, & Webber, 2002). When the time delay and embedding dimension were not equal, we used the larger values (Marwan et al., 2007). The input parameter *radius* was determined by using graphic visualization to determine which values were appropriate to yield an approximately 1% recurrence rate (Webber & Zbilut, 2005; Zbilut, et al., 2002). Knee angles between actors were compared using CRQA.

Results and Discussion

Data were analyzed using Friedman's nonparametric test. While %REC values remained stationary across states (see Table 1), there were notable increases in %DET when the participants' limbs were in synchrony (inphase and antiphase) relative to in transition (while the overall effect was non-significant, the distribution of results suggests that a lack of significance may likely be attributed to statistical power). Increases in %DET indicate that the structure of coordination became more deterministic when participants entered one of the two stable forms of synchrony. This was further highlighted by results that showed that periods of synchrony tended toward greater stability (measured by Maxline) and periodicity (Meanline) than periods of transition. A similar pattern of effects was uncovered for measures of Entropy, $\chi^2(2)= 9.58$, $p < .01$, where antiphase coordination showed greater complexity than the other two states.

Table 1. CRQA average results of all dyads, per coordination state (inphase, transition, antiphase).

State	Inphase	Transition	Antiphase
Delay	15.50 ± 5.61	10.00 ± 1.67	14.40 ± 1.67
Embedding	3.67 ± 0.52	3.00 ± 0.89	4.40 ± 1.67
Radius	20.00 ± 3.99	14.50 ± 4.89	23.30 ± 5.69
%REC	1.04 ± 0.04	1.05 ± 0.04	1.04 ± 0.02
%DET	96.51 ± 1.76	91.92 ± 5.15	97.62 ± 1.54
%DET/%REC	92.79 ± 4.93	87.54 ± 5.25	93.29 ± 2.83
Entropy	3.00 ± 0.44	2.39 ± 0.64	3.27 ± 0.43
Relative Entrophy	0.68 ± 0.11	0.62 ± 0.10	0.70 ± 0.16
Maxline	25.00 ± 10.90	16.33 ± 8.91	31.20 ± 17.36
Meanline	5.06 ± 0.74	4.46 ± 1.99	5.94 ± 1.91

In sum, the results reveal that the non-intentional coordination between two children was more deterministic, periodic, and stable when in synchronization than when out of synchronization. Interestingly, antiphase coordination tended to exhibit greater complexity, periodicity, and stability than inphase coordination. While a lack of statistical significance leaves these results in question, one possible interpretation may be that the antiphase state, exhibiting more complexity than the inphase state, consequently evolved to a greater periodicity during the maintenance of the coordination. Further investigation is required to confirm. Nonetheless, the present study adds further support for cross recurrence analysis as a tool for the detection of periodicity and determinism during interpersonal non-intentional synchronization in children.

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