A Heart for Interaction: Physiological Entrainment and Behavioral Coordination in a Collective, Creative Construction Task

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Abstract

Interpersonal physiological entrainment is increasingly argued to underlie rapport, empathy and even team performance. Inspired by the model of interpersonal synergy, we investigate the presence, temporal development, possible mechanisms and impact of interpersonal heart rate entrainment during individual and collective creative LEGO construction tasks. In Study 1 we show how HR entrainment is driven by a plurality of sources including task constraints and behavioral coordination. Generally, HR entrainment is more prevalent in individual trials (involving participants doing the same things) than in collective ones (involving participants taking turns and performing complementary actions). However, when contrasted against virtual pairs, collective trials display more stable HR entrainment supporting the idea that online social interaction plays a role. Furthermore, HR entrainment is found to grow across collective but not individual trials. In Study 2 we further show that in collective trials the dynamics of HR entrainment is statistically predicted by interpersonal speech and building coordination. In Study 3, we explore the relation between HR entrainment, behavioral coordination, and rapport and perceived group competence. While behavioral coordination predicts rapport and group competence, HR entrainment does not. Physiological entrainment, thus, should not be considered a universal unmediated proxy for shared emotions, empathy and collective performance, but should be considered within the constraints and functional demands of the ongoing activity. Behavioral coordination – at least in tasks requiring forms of joint action – seems to be more informative of both physiological entrainment and collective experience.

Keywords: interpersonal coordination; joint action; common ground; physiological entrainment; behavioral coordination; heart rate; emotional arousal; interpersonal synergy.

1. Introduction

As we go through our day, we continuously engage socially with other people: from chats at the bus stop, to joint projects at the work place, and nurture of long term relations with friends and family. What these very different social activities all have in common, is that they depend, to varying degrees, on our ability to emotionally engage, align and closely coordinate actions with one another. Which processes are involved in the development of such coordination and rapport? Several studies have investigated aspects of complex coordinative dynamics - from mutual adaptations of movements, words and prosody (Fusaroli et al., 2012; Riley, Richardson, Shockley, & Ramenzoni, 2011), to establishment of shared routines (Fusaroli, Raczaszek-Leonardi, & Tylén, 2014; Mills, 2014) – and their role in facilitating performance and rapport (Marsh, Richardson, & Schmidt, 2009). Moreover, a growing number of studies points to the crucial role of physiological entrainment: Interpersonal coupling has been observed at the level of brain activity (Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010; Friston & Frith, 2015; Hasson, Ghazanfar, Galantucci, Garrod, & Keysers, 2012; Konvalinka et al., 2014; Pickering & Garrod, 2013), but also low level physiological processes such as heart rate (henceforth HR) is found to become increasingly interdependent, presenting more and more similar temporal dynamics. HR entrainment, in particular, is argued to underlie emotional common ground in social interactions, as it facilitates the construction of a sense of community (Konvalinka et al., 2011), empathy and mindreading (Levenson & Gottman, 1983; Levenson & Ruef, 1992) and even team performance (Elkins et al., 2009; Henning, Boucsein, & Gil, 2001; Henning & Korbelak, 2005; Strang, Funke, Russell, Dukes, & Middendorf, 2014; Wallot, Mitkidis, McGraw, & Roepstorff, submitted).

However, no coherent framework has yet been developed to unravel the factors and impact of HR entrainment and its role in diverse kinds of social interactions. Is HR entrainment a property of mundane, everyday interactions? Is it a necessary condition for emotional common ground and rapport? And what are the mechanisms underlying it?

A recent model – the Interpersonal Synergy Model (Fusaroli, Raczaszek-Leonardi, et al., 2014; Fusaroli & Tylén, in press; Riley et al., 2011) – provides a constructive starting point for an articulated investigation of HR entrainment in the context of social interactions. According to the Interpersonal Synergies Model, interpersonal coordination is functional. That is, the behavior of interacting agents becomes interdependent (A's behavior impacts B's behavior, which in turn impacts A's behavior) in ways that are shaped by their goals and activities. In other words, different tasks call for different ways of interacting and the group performance and experience will be related to how well the interpersonal coordination meets these task affordances.

Inspired by the synergy model, we devised a series of three studies to investigate the relation between task constraints and behavioral coordination on HR entrainment in the specific context of creative collaborative tasks. This allows us to better understand the conditions, possible mechanisms and impact of HR entrainment in the contexts of collaborative tasks, integrating this line of research with that on behavioral coordination.

In the following we will review the current literature on HR entrainment to identify which mechanisms and impact have been found, before detailing our studies and their findings.

1.1 HR entrainment

A central aspect of human social coordination and collaboration concerns the way interacting individuals form group-level behaviors, for instance indexed by co-regulation of their emotional states. Heart rate is a useful measure in this regard as it has been shown to increase with emotional arousal in ways that are emotion-specific (Ekman, Levenson, & Friesen, 1983; Levenson & Ruef, 1992; Schwartz, Weinberger, & Singer, 1981; Sinha, Lovallo, & Parsons, 1992). Heart rate is also connected with different aspects of behavior. Heart rate increases with physical activity (Wallot, Fusaroli, Tylén, & Jegindø, 2013) and it is (weakly) entrained to respiration rhythms (Schäfer, Rosenblum, Kurths, & Abel, 1998; Yasuma & Hayano, 2004). In other words, as interacting agents get to coordinate their behaviors and share emotional ground, we have reasons to expect their HR to become increasingly entrained.

Such intuitions have guided investigations of collective high emotional arousal in diverse social contexts: Di Mascio and colleagues (1955) showed shared co-variation between patient and psycho-therapist, and Levenson and Gottman (1983) observed high levels of physiological entrainment during couple therapy, although mostly in distressed couples during episodes involving negative emotions. Helm and colleagues (2012) found HR entrainment in romantic couples across a series of tasks aimed at eliciting shared emotional arousal. Müller and Lindenberger (2011) found similar patterns among choir singers, modulated by specific types of vocal coordination. Furthermore, Konvalinka and colleagues (2011) investigated HR entrainment in a high arousal context: a religious fire-walking ritual. Here HR entrainment was even found among participants doing quite different things: Individuals walking on burning coals and spectating family members shared a high level of entrainment, while this was not shared with unrelated spectators.

A second line of research focused on more task-oriented collaborative settings, investigating the connection between HR entrainment and group performance. Henning and colleagues (Henning, Armstead, & Ferris, 2009; Henning et al., 2001) showed that in collaborative maze-game and room-clearing tasks, teams displaying higher HR entrainment solved the task faster and with fewer mistakes. As HR entrainment also correlated with self-reports of team coordination, task engagement, and performance (Gil & Henning, 2000), the researchers argued that it reflected increased team situation awareness, intra-team coordination, and shared mental models. To reinforce this point, Henning and Korbelak (2005) repeated the experiments introducing a disruption: at random times the team roles were re-organized. Immediately before such perturbations, HR entrainment positively predicted post-perturbation performance.

However, these results have recently been challenged. Strang and colleagues (2014) report a negative correlation between HR entrainment, team performance and team attributes during a collaborative Tetris-like task. Analogously, Wallot and colleagues (submitted) report HR entrainment to be negatively correlated with self-reports of collaborative satisfaction, and external raters' judgment of output product quality in a joint LEGO construction task.

HR entrainment can thus be found in a variety of interpersonal contexts; however, the connection between heart rate, experience and collective performance seems far from a simple one. Many issues are still open and there is currently no consensus as to the factors regulating and impacting the level and dynamics of HR entrainment.

1.2 Contexts of HR entrainment

A first crucial issue concerns the mechanisms behind HR entrainment. It is clear that hearts (or autonomic systems in general) are not linked in any direct way. Nor are they easily intentionally coordinated. In other words, important questions regard the mediating factors enabling and facilitating HR entrainment. The previously reviewed literature points to several possibly interacting factors: i) the co-presence and history of previous interactions; ii) the structure of the task that the interacting agents are sharing; iii) degree of behavioral coordination between agents.

Simply being co-present in a situation has been observed to elicit behavioral and emotional contagion between individuals (Chartrand & Bargh, 1999; Hatfield & Cacioppo, 1994). People spontaneously mimic each other's behaviors and facial expressions, which can lead to the sharing of emotional states, with concomitant shared physiological arousal. Some studies of HR entrainment exploit this dimension of co-presence, focusing on how sharing the same situation induces shared physiological arousal in a way that is mediated by the history of previous interactions. For instance, being in a social, familiar or romantic relationship facilitates the entrainment of shared HR dynamics (Chatel-Goldman, Congedo, Jutten, & Schwartz, 2014; Helm et al., 2012; Konvalinka et al., 2011; Levenson & Gottman, 1983).

However, in most studies people are not simply co-present, but share an activity. In these studies, people have to engage in a computer mediated tasks (Henning et al., 2009; Henning et al., 2001; Henning & Korbelak, 2005; Strang et al., 2014), in the physical construction of a LEGO model (Wallot et al., submitted), or in choir singing (Müller & Lindenberger, 2011). Each of these activities implies diverse constraints on the behaviors of the participants: sitting, being concentrated, breathing with a certain rhythm, etc. That fact that HR is influenced by activity and respiration might motivate the prediction that the task alone, by constraining participants' behaviors, drives important aspects of the HR entrainment.

Finally, it has been pointed out that people entrain their behaviors in complex ways in contexts of social interactions: interacting individuals entrain their postural sways (Shockley, Santana, & Fowler, 2003), align to each other's behaviors and linguistic forms and complement each other's action (Dale, Fusaroli, Duran, & Richardson, 2013; Fusaroli, Raczaszek-Leonardi, et al., 2014; Fusaroli & Tylén, in press). Thus beyond mere co-presence and task constraints, online behavioral coordination might promote HR entrainment, for instance by synchronizing behaviors more than the task alone would afford (Louwerse, Dale, Bard, & Jeuniaux, 2012). Moreover, some studies suggest that synchronization of similar behaviors might not be necessary for HR entrainment, as shared arousal and coordination of complementary behaviors might do the trick (Henning et al., 2009; Konvalinka et al., 2011; Strang et al., 2014).

1.3 Impact of HR entrainment

A second open issue concerns what we can learn about human social relations, coordination, and collaboration from observations of HR entrainment. Henning and colleagues (Gil & Henning, 2000; Henning et al., 2009; Henning et al., 2001; Henning & Korbelak, 2005) argue that HR entrainment, by reflecting team members' sensorimotor and emotional integration, is indicative of the team's collaborative skills to the point that it can predict future performance. Other research, however, suggests caution as HR entrainment can also be driven by negative emotions (Levenson & Gottman, 1983), and dysfunctional team coordination and experiences (Strang et al., 2014; Wallot et al., submitted).

1.4 The structure of the investigation

To investigate these open issues from an interpersonal synergy perspective, we designed an experimental study of HR and behavioral coordination in a creative construction activity in which we manipulated task constraints and assessed the participants' compliance to them. The experimental setup was inspired by the intervention method LEGO Serious Play (Gauntlett, 2007): Groups of participants repeatedly built LEGO models illustrating their understanding of six abstract notions. Sometimes they build the models collaboratively as a group, sometimes as individuals. We could thus compare the constraints of two different versions of the tasks: Individual constructions afforded high similarity of behaviors without online interaction. Collective constructions afforded less similar behaviors, but encouraged the development of coordinative routines and strategies: group members could not all build or talk at the same time but had to coordinate their actions, negotiate joint understanding and resolve disagreements in order to complete the assignments (Bjørndahl, Fusaroli, Østergaard, & Tylén, 2014, in press).

Relying on this setup, we devised three studies, to successively investigate the previously highlighted questions. In study 1, we focus on co-presence and task impact on HR entrainment, contrasting individual constructions requiring similar activities and collective constructions requiring actual coordination between group members in terms of complementary speech and building actions. In study 2 we further investigate the role of behavioral proxies through which HR entrainment can be established and maintained, by attempting to predict HR entrainment based on the levels of building and speech coordination. In study 3 we explore the predictive power of physiological entrainment and behavioral coordination for the self-reported experience of the interactions, in particular focusing on group members' experiences of relatedness and group performance.

2. Study 1 - Heart Rate Entrainment

In study 1, we investigated the presence of and conditions for HR entrainment according to a 2-by-2 experimental design. Groups of 4-6 participants had to repeatedly construct LEGO models individually and collectively. In both conditions we contrasted HR entrainment pairwise between participants co-present at the same table (real pairs) and in pairs artificially constructed by selecting participants from two different groups, thus sharing the task, but not any actual co-presence or interaction (virtual pairs). We designed this setup to investigate three hypotheses.

Hypothesis 1: Co-presence. If co-presence is crucial in facilitating HR entrainment, we will observe higher HR entrainment in real pairs than in virtual pairs, across individual and collective tasks.

Hypothesis 2: Task-related constraints. If task-related constraints are the driving force behind HR entrainment, we will observe no significant difference between HR entrainment in real and virtual pairs across individual and collective tasks.

Hypothesis 3: Behavioral coordination. If actual interpersonal behavioral coordination is driving HR entrainment, we will observe higher coordination in real pairs during collective, but not individual construction tasks. As behavioral coordination is likely to be established and develop over time, as participants develop turn-taking routines and strategies to co-build models (Bjørndahl et al., in press; Mills, 2014), we also predict increase in real pairs' HR entrainment over time in collective, but not in individual construction tasks.

It should be noted that these hypotheses are not fully independent, and that we expected to find multiple interacting sources of HR entrainment. In particular, the interpersonal synergy model strongly motivates hypotheses 2 and 3: Task constraints are a defining feature of the model and construction tasks crucially involve behavioral coordination.

2.1 Materials and Methods

2.1.1 Participants

30 participants (15 f, mean age 23.6, sd 2.6) were recruited among students of Aarhus University and received monetary compensation for their participation (ca. 50 $). All participants were native speakers of

Danish. Participants were organized in mixed-gender groups of four to six, randomly assembled. Group members did not know each other in advance.

2.1.2 Design and Procedure

Upon arrival, participants were strapped with heart rate monitor belts and wireless Lavalier microphones. Participants were placed around a table (fig 1) and familiarized with the materials and task through two practice trials. Two cameras video-recorded the group activities from different angles.

Figure 1 – Experimental setup with five participants sat around a table collectively building a LEGO model

The actual experiment was carried out as a two-condition within-group contrast: collective vs. individual. Each group underwent an interleaved series of six individual and six collective LEGO constructions of five minutes each, during which their heart rate coordination was measured. In each trial, participants were instructed (in Danish) to use LEGO blocks to construct their understanding of one of six abstract concepts: ‘responsibility’ (ansvar), ‘collaboration’ (samarbejde), ‘knowledge’ (viden), ‘justice’ (retfærdighed), ’safety’ (tryghed) and ‘tolerance’ (tolerance). The concepts were selected to be sufficiently common in public discourse that participants would know and have an opinion about them, but still challenging to construct in LEGOs. The LEGO materials were in all cases a LEGO Serious Play Starter Kit consisting of 214 mixed pieces (standards bricks in varying shapes and colors, wheels, LEGO people, etc.). In order to constrain variability of complexity and size of the models, participants were instructed to build their models within the limits of an A5 (5.8 x 8.3 inch) piece of cardboard (for an example of LEGO creations, see fig 2).

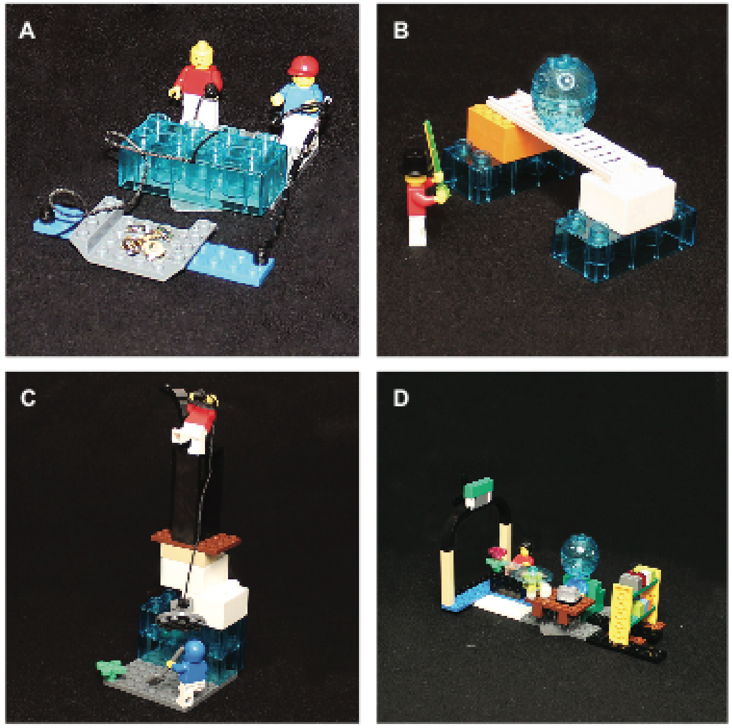

***Figure 2** –Examples of LEGO models. **A**: Collective model illustrating "Collaboration". **B**: Collective model illustrating "Justice". **C**: Collective model illustrating "Responsibility". **D**: Collective model illustrating "Knowledge".*

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Every concept was built twice, in succession, individually and collectively. The order was counterbalanced between trials. In individual trials, participants sat quietly and constructed their own models. In collective trials participants freely interacted to construct joint models. As the overall procedure took over 3 hours, the experiment was divided in two 3-concept sessions separated by a 20 min. break. For more details on the interactions during such collective tasks, cf. (Bjørndahl et al., 2014, in press).

2.1.3 Heart Rate Activity

Polar Team2 (Polar, 2013) chest-strapped heart rate monitors were used to record participants' heart beat activity as R-R intervals with millisecond accuracy. To align heart beat activity across participants we generated equally sampled time-series by estimating beats per minute every second based on sliding 5-

second windows (Wallot et al., 2013). We isolated 5-minute HR sequences corresponding to the 12 construction tasks.

2.1.4 Data Analysis: Interpersonal HR Entrainment

HR time series present non-stationary dynamics. In other words, their means and standard deviations may vary over time as a function of e.g. activity, respiration and emotional arousal (Malik et al., 1996; Sayers, 1973). For this reason, linear methods assuming data stationarity, such as for instance correlation, are not appropriate to assess interpersonal HR entrainment. Additionally, interpersonal HR dynamics have been shown to display continuously varying lags of entrainment (Strang et al., 2014), which require a method able to deal with such complexity and not assuming constant lags. We therefore chose to employ *Cross Recurrence Quantification Analysis*, a method developed to quantify the shared dynamics of complex non-linear systems. With this method we were able to produce several metrics with which to estimate the similarity between different dynamical patterns and capture many properties of the heart rate dynamics that would otherwise be lost due to averaging with more traditional correlation analysis (for more details on the methods, cf. (Fusaroli, Konvalinka, & Wallot, 2014; Marwan, Carmen Romano, Thiel, & Kurths, 2007). Relying on two time-series, CRQA reconstructs the phase space of possible combination of states and quantifies the structure of recurrence, that is, of the instances in which the two time-series display similar dynamics, controlling for individual baselines of HR. CRQA has been previously used successfully to assess HR entrainment (Konvalinka et al., 2011; Strang et al., 2014; Wallot et al., 2013) and allowed us to quantify, amongst other things:

- *Level of coordination*, defined as the percentage of values that are repeated between the two time series (recurrence rate, RR). The higher the recurrence rate, the more similar the range of values displayed by the participants' HRs.
- *Stability of coordination*, defined as average length of sequences repeated across time-series (L). The higher the L, the more the participants tend to display prolonged and stable sequences of HR entrainment.

CRQA was calculated using the CRP Toolbox for Matlab 2014a. The phase space parameters were calculated according to Abarbanel (1996): the delay was set to minimize mutual information, and the embedding dimensions to minimize false nearest neighbors across all time-series. The threshold of recurrence was set to ensure an average recurrence rate comprised between 0.04 and 0.10 (Marwan et al 2007).

2.1.5 Data Analysis: Virtual vs. Real Pairs

To assess the presence of interpersonal HR entrainment we calculated CRQA indexes for all possible pairs of members within each group (within-group real pairs). Per each real pair we then randomly selected a participant and paired her with a participant from a different group, thus generating between-groups virtual pairs. This procedure generated 56 real pairs and 56 virtual ones, measured during each of the 6 collective and 6 individual trials. Since we excluded HR time series in which the sensor lost contact for more than 5 seconds, we ended up with a total of 1306 data points (out of 1344 possible).

2.1.6 Data Analysis: Assessing the Presence and Temporal Development of HR Entrainment

In order to assess Hypotheses 1 to 3, that is, comparing the level and stability of HR entrainment according to the experimental manipulations, we employed mixed effects linear models, controlling for group and pair variability, as well as for order of conditions and possible session effects (as participants took a break midways through the experiment). Each index of HR entrainment (RR and L) was separately employed as dependent variable; activity (individual vs. collective), virtual vs. real, session and order of condition were used as fixed effects, pair and group were used as random effects including random slopes for activity and virtual vs. real. Given the limited amount of degrees of freedom in the data, we only looked at interactions between activity and virtual vs. real. Notice that the random effects structure constrains the degrees of freedom in the same way as a multi-level repeated measures model.

In order to assess the second part of Hypothesis 3, that is, the development of level and stability of HR entrainment over time in the two experimental conditions, we again constructed a mixed effects linear model. Each index of HR entrainment (RR and L) was separately employed as dependent variable; activity, time (trial), session and order of condition were used as fixed effects, pair and group variability were used as random effects including random slopes for activity and time. Given the limited amount of degrees of freedom in the data, we only looked at interactions between activity and time. Post-hoc testing was performed to assess differences between individual and collective activity at time 1 and at time 6. All models were tested for influential observations and normality of the residuals, and the assumptions were respected, unless otherwise reported. Values reported and confidence intervals were based on bootstrapped analyses stratified by pair, group and tasks. Variance explained by the model was quantified using R^2: both marginal, indicating the variance explained by fixed effect; and conditional, indicating the variance of the full model (fixed and random effects) (Johnson, 2014). Mixed effects models analyses and plot were performed using the lme4, MuMIn, boot and ggplot2 packages for R (3.1).

2.2 Results

2.2.1 Assessing the Presence of Physiological Entrainment

The level of HR entrainment displayed a significant main effect of activity with higher overall entrainment during individual (0.081, CI: 0.078, 0.084) than during collective construction tasks (0.071, CI: 0.069, 0.074). In other words, participants' heart rate shared similar variability and dynamics, as expressed by RR, 8% (individual) and 7% (collective) of the time, across all possible time lags. However, real vs. virtual pairs did not show any significant difference, nor an interaction with activity. Order was a significant factor, indicating that in general pairs starting with a collective construction tasks would show higher level of HR entrainment. Session was not a significant factor. For more details, cf. Table 1.

Table 1: Level of HR entrainment

Variable	Factor	ß	SE	p-value
RR	Real	0	0	0.25
R^2m=0.04	Activity	-0.01	0	0.002*
R^2=0.18	Interaction	0	0	0.91
	Order	0.01	0.01	0.04*
	Session	0.01	0	0.13

The stability of HR entrainment displayed significant main effects and interactions of activity and real vs. virtual pairs. HR entrainment was significantly more stable during individual (4.751, CI: 4.619, 4.905) than during collective construction tasks (4.383, CI: 4.268, 4.498). In other words, pairs during individual trials maintained HR entrainment for longer uninterrupted sequences than pairs during collective trials, with an average difference of ca. 0.4 recurrence points, corresponding to ca. 1.6 seconds. HR entrainment was also significantly more structured in real compared to virtual pairs. However, the latter effect was largely driven by an interaction, where real pairs had a significantly more structured HR entrainment than virtual pairs during collective (real: 4.801, CI: 4.678, 4.961; vs. virtual: 3.638, CI: 3.518, 3.765; a difference of ca. 4.8 seconds), but not during individual activity (real: 4.841, CI: 4.639, 5.069; vs. virtual: 4.660, CI: 4.497, 4.857). Order of condition did not significantly impact the structure of HR entrainment, but session did, as the second session displayed a higher stability of HR entrainment. For more details cf. Table 2.

Table 2: Stability of HR entrainment

Variable	Factor	ß	SE	p-value
L	Real	0.9	0.13	<0.0001*
R^2m=0.13	Activity	-0.38	0.17	0.03*
R^2=0.25	Interaction	1.42	0.16	<0.0001*
	Order	0.07	0.18	0.69
	Session	0.29	0.1	0.0049*

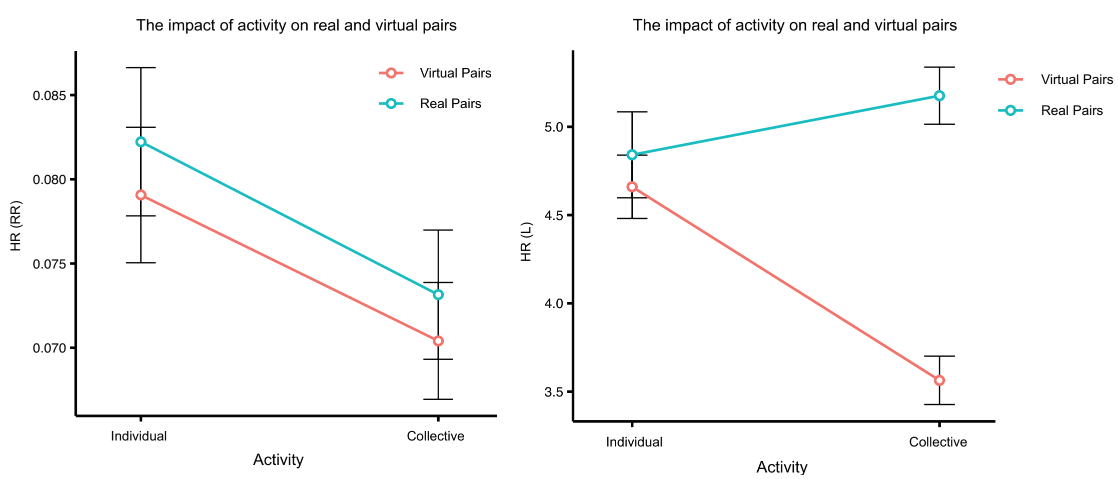

Figure 3 – Impact of activity on HR entrainment. Panel a on the left represents levels of HR entrainment individual and collective constructions and in real and virtual pairs. Panel b on the right analogously represents stability of HR entrainment.

Temporal Development of Coordination

The level of HR entrainment displayed significant main effects of activity and time. Collective activity generated lower entrainment (0.073, CI: 0.070, 0.077) than individual (0.082, CI: 0.078, 0.086). Across conditions, the general level of HR entrainment displayed decrease over time. However, the significant interaction between activity and time reveals that the level of HR entrainment increases over time during collective activity (ß =0.01, SE=0.002, p=0.03), while it decreases during individual activity (ß =-0.01, SE= 0.005, p=0.015). Cf. Table 3. Notice in particular that during the initial constructions, the level of HR entrainment is higher for individual constructions (0.10, CI=0.09 0.11) than for collective constructions (0.07, CI= 0.07 0.08). However, during the final constructions the temporal developments make individual and collective constructions display very similar levels of HR entrainment (individual: 0.07, CI=0.06 0.08; collective: 0.08, CI= 0.07 0.09).

Table 3: Level of HR entrainment over time

Variable	Factor	**ß**	SE	p-value
RR	Activity	-0.01	0.006	0.0007*
R^2m=0.06	Time	-0.01	0.003	0.001*
R^2=0.21	Order	0.01	0.006	0.07
	Session	0.02	0.006	0.002*
	Activity*Time	0.004	0.001	0.0081*

The stability of HR entrainment displayed significant main effects of activity and time. Collective activity generated less structured entrainment (4.802, CI: 4.678, 4.961) than individual (4.841, CI: 4.639, 5.069), though the effect was only statistically significant when controlling for session and order of conditions and corresponded to a difference in 1% recurrence rate. The significant interaction between activity and time reveals that the stability of HR entrainment increases over time during collective activity (ß =0.25, SE=0.11, p=0.018) but not during individual activity (ß =-0.53, SE=0.36, p=0.139). Cf. Table 4. Notice again that during the initial constructions, the level of HR entrainment is higher for individual constructions (5.66, CI=5.24 6.11) than for collective constructions (4.28, CI=4.09 4.53), with a difference of ca. 6

seconds. However, during the final constructions the temporal developments make collective constructions display a higher stability of HR entrainment (5.97, CI=5.73 6.24) than individual ones (4.71, CI= 4.39 5.11).

Table 4: Stability of HR entrainment over time

Variable	Factor	ß	SE	p-value
L	Activity	-0.89	0.36	0.003*
R^2m=0.04	Time	-0.49	0.18	0.006*
R^2=0.18	Order	0.1	0.24	0.69
	Session	0.68	0.48	0.15
	Activity*Time	0.24	0.07	0.0008*

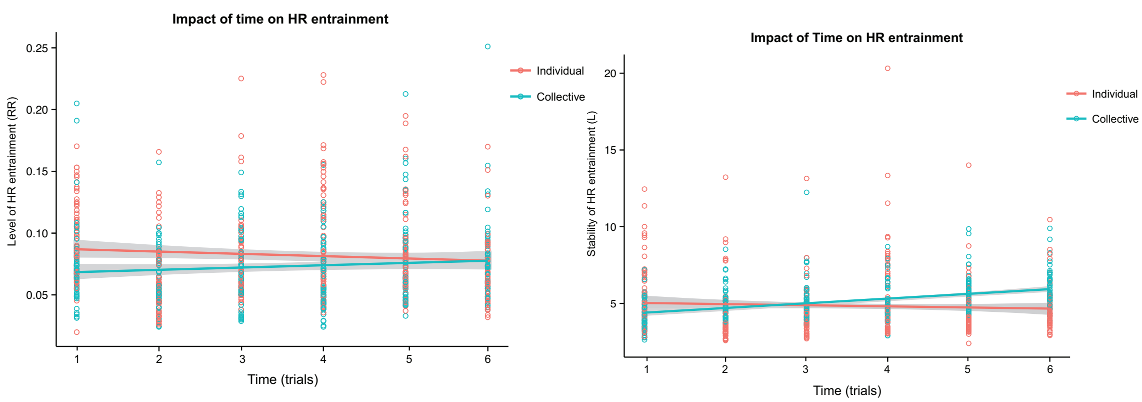

Figure 4 – Impact of time and activity on HR entrainment. Panel a on the left represents level of entrainment and panel b on the right stability of entrainment.

2.3 Discussion

The results support a combination of Hypothesis 2 and 3. We do not observe a general effect of co-presence across individual and collective activity, neither in level nor in stability of HR entrainment. However, task-constraints and online coordination seem to play a decisive role. The level of HR entrainment is largely driven by task constraints: engagement in the task makes participant entrain their heart rates irrespective of whether they are co-present or not as revealed by the fact that there was no significant difference between real and virtual pairs. Additionally, the significant difference between level of HR entrainment in individual and collective activity, points to different task constraints in these two conditions: while in individual constructions, participants do quite similar things (quietly concentrate on each their individual LEGO model), in collective constructions, participants often structure their activities in more complementary ways (taking turns in talking and listening, holding the model, searching for and adding bricks, etc.).

The stability of HR entrainment adds an interesting perspective to the story: while the overall level of HR entrainment is lower in collective trials, the stability is the same as in individual trials, for real pairs, but lower for virtual pairs. This suggests that actual online collaboration has an impact on HR entrainment above and beyond simple task constraints as collaborative tasks involve not just similar individual levels of engagement (being equally physiologically aroused), but repeated, prolonged sequences of entrained physiological dynamics. This hypothesis is further supported by the general increase in level and stability of HR entrainment over the course of collective but not individual trials; possibly as a function of coordinative routines being established. In collective constructions, not only the level of HR entrainment reaches individual constructions levels, but the stability becomes significantly higher.

3. Study 2: From behavioral coordination to physiological entrainment

Study 1 supported the hypothesis that certain aspects of interpersonal HR entrainment, in particular its stability, are related to actual online interpersonal interaction during the collective construction tasks. In order to further explore this hypothesis, we devised a second study more directly quantifying behavioral coordination and its relation to HR entrainment.

The collective construction of LEGO models requires at least two aspects of behavioral coordination: 1) participants have to discuss and agree upon their joint project, which requires taking turns in dialogical interaction; 2) participants cannot all manipulate the model at the same time but have to coordinate their actions in physically building the model. We have already discussed how motor activity impacts HR arousal (Wallot et al., 2013). Speech activity is also likely to pose strong constraints on HR. Speaking has considerable effects on respiratory patterns, involving rapid inspiratory and prolonged expiratory phases (Hoit & Lohmeier, 2000; McFarland & Smith, 1989; Winkworth, Davis, Adams, & Ellis, 1995). More crucially, conversations constrain the temporal structure of individual speech contributions in turn taking. Moreover, interlocutors involved in conversation have been shown to spontaneously adapt to each other's linguistic forms, conversational moves, syntax and prosody (Hopkins, Yuill, & Keller, 2015; Pickering & Garrod, 2004; Wilson & Wilson, 2005), which may also lead to the development of interactional routines and procedural conventions (Fusaroli & Tylén, in press; Mills, 2014). By using more similar linguistic forms and coordinating the timing of their speech behavior, interlocutors come to tightly interweave their breathing patterns (McFarland, 2001; Warner, Waggener, & Kronauer, 1983), which in turn have been shown to affect HR (Beda, Jandre, Phillips, Giannella-Neto, & Simpson, 2007; Berntson, Cacioppo, & Quigley, 1993).

Although no study, to our knowledge, has assessed the relative impact of the different behavioral modalities, it seems likely that the development of shared engagement, turn-taking and routines in speech and building activity impact HR entrainment. In pursue of this hypothesis, Study 2 used the audio and video recordings of the Lego construction tasks to quantify interpersonal coordination of building and speech activity (BA and SA) and assessed its relation to HR entrainment.

3.1 Materials and Methods

3.1.1 Speech and Building Coding In order to investigate the potential mechanisms enabling heart rate coordination we quantified speech and building coordination during collective trials. Employing the coding software ELAN (Wittenburg, Brugman, Russel, Klassmann, & Sloetjes, 2006), two research assistants naive to the purpose of the study carefully screened the videos of the collective tasks and separately coded for presence (1) and absence (0) of speech and building activity for each participant on a second-by-second basis. The coding procedure thus provided us with a rough index of when and for how long individual participants were engaged in speech or building. Notice, however, that the way we capture the structure of engagement is insensitive to the specific speech and building behaviors at play. The coded data consisted of 30 participants engaged in 6 collective trials (of five-minutes), which generated 170 speech engagement and 170 building engagement time series out of 180 total, the missing data being due to corrupted audio and video materials. Notice that the videos have also been analyzed qualitatively, with other research purposes in (Bjørndahl et al., 2014, in press).

3.1.2 Speech and Building Coordination Interpersonal coordination in speech and building engagement was quantified using CRQA on the nominal (1s and 0s) time series. While initially developed for numeric time-series CRQA has been widely employed for nominal time series (Dale, Warlaumont, & Richardson, 2011; Fusaroli & Tylén, in press; Louwerse et al., 2012; Reuzel et al., 2013). Analogously to study 1, CRQA allows us to quantify the level (RR) and structure (L) of shared behavioral engagement. Importantly, since CRQA assesses shared dynamics across multiple time-lags, it goes beyond simple synchrony – e.g. including stable patterns of turn-taking. Parameters for CRQA were set according to Dale and colleagues (2010): embedding dimensions were set to 2, delay to 1 and threshold to 0. As we were interested in shared engagement, and not in recurrence of inactivity, we “blanked out” each participant’s time series so that 0’s would not recur with each other. We generated 56 real pairs assessed through 6 collective trials amounting to 320 data points (16 had to be excluded due to corrupted audio-video materials). The procedure was otherwise analogous to Study 1.

3.1.3 Data Analysis: Assessing the Role of Behavioral Coordination on Physiological Entrainment In order to assess the relation between behavioral coordination and physiological entrainment, we employed mixed effects linear models with each of the indexes of heart rate coordination (RR and L) as dependent variable, all four indexes of speech (Speech RR and L) and building (Build RR and L) coordination as fixed effects. We used only random intercepts for group and pair variability, as the models with random slopes did not converge. The model employed 310 data points, as we had to exclude data points where either HR entrainment or behavioral coordination values were not present. The procedure was otherwise analogous to Study 1.

3.2 Results

The level of heart rate coordination (HR RR) was significantly related to the level of building and the stability of speech coordination (Build RR and Speech L): the more the building and the more stable the speech coordination, the more heart rate entrainment (cf. Table 5 and Figure 5a). The stability of heart rate coordination (HR L) was significantly related to speech coordination: the more frequent (RR) and stable (L) the speech coordination, the more stable the heart rate entrainment (cf. Table 5 and Figure 5b).

Table 5: From Behavioral Coordination to Physiological Entrainment

Variable	Factor	ß	SE	p-value
HR RR	Build RR	0.23	0.12	0.045*
R^2m=0.14	Build L	≈0	≈0	0.248
R^2=0.23	Speech RR	0.01	0.01	0.456
	Speech L	≈0	≈0	0.0013*
HR L	Build RR	2.04	4.19	0.63
R^2m=0.37	Build L	-0.16	0.09	0.077
R^2=0.47	Speech RR	1.77	0. 45	<0.0001*
	Speech L	0.02	≈0	<0.0001*

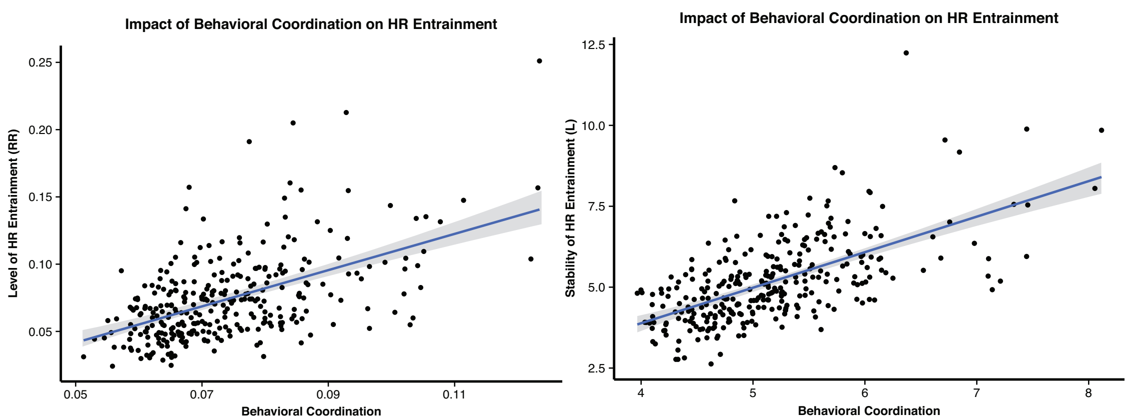

Figure 5: From Behavioral Coordination to Physiological Entrainment: In the first panel on the left we represent the model predictions against the level of HR entrainment scores. In the second panel on the right we represent the model predictions against the stability of HR entrainment scores.

3.3 Discussion

While study 1 showed that the level of HR entrainment was mainly driven by task structure, we also observed that HR stability in collective activity was higher in real than in virtual pairs indicating the role of actual online behavioral coordination. Study 2 supports the hypothesis that HR entrainment is (also) driven by online behavioral coordination: the level and stability of speech and building coordination, based on video coding, positively predict HR entrainment dynamics. While the level of HR entrainment is weakly

(2% of the variance) but significantly predicted, its structure is more strongly predicted (25% of the variance explained). The results also point to an intriguing complexity of mechanisms: the level of physiological entrainment is related more to motor coordination (building), while its structure is connected to speech coordination. Building and speech coordination thus seem to contribute to HR entrainment in complementary ways.

4. Study 3 – Coordination, Entrainment and Experience

While study 2 supported the hypothesis that HR entrainment is – at least partially – driven by behavioral coordination, another concern regards how participants' subjective experience of the collaborative interactions relates to behavioral coordination and HR entrainment. In previous studies, behavioral coordination and HR entrainment have each been separately related to the phenomenological experience of social interactions (Gil & Henning, 2000; Marsh et al., 2009). However, as HR entrainment is mediated through behavioral coordination, and the latter is essential to solve the task at hand, behavioral coordination might be expected to outperform the physiological entrainment in predicting experiential variables. In light of this, in Study 3 we compared the predictive power of behavioral coordination and physiological entrainment on self-rated experience. In particular, we focused on the participants' experiences of relatedness to their fellow group members and assessment of their group's competence in solving the task.

4.1 Materials and Methods

4.1.1 Experience of the Collaboration The creative LEGO construction tasks did not afford objective analysis of performance. However, general correlations between group cohesion, self-reported competence and externally measured performance have often been reported (Lyons, Funke, Nelson, & Knott, 2011; Paskevich, Brawley, Dorsch, & Widmeyer, 1995). In order to provide such insight into group members' experience of the creative collaboration, at the end of the experiment all participants filled in a customized version of the Intrinsic Motivation Inventory (Ryan, 1982), slightly modified to capture: i) *Relatedness to the group* and ii) Perceived *collective competence*.

4.1.2 Data Analysis: From Coordination to Experience As experience was measured at the level of individual participants but referred to their experience of the group, we calculated an individual coordination index, by averaging all within-group pairs to which that individual participated. In order to assess the potential impact of behavioral and physiological coordination on experience we employed mixed effects linear models with the 2 indexes of experience separately as dependent variables, and the individual indexes of interpersonal coordination as fixed factors, while group was a random factor. As experience was assessed at the end of the experiment, we chose to employ indexes of interpersonal coordination from the last trial of the experiment. The models involved 23 datapoints, as the recordings of group 1's last task was corrupted and one participant from group 5 did not complete the questionnaire

4.2 Results

Self reported relatedness was significantly predicted by the stability of building and speech coordination: the more stable building and the less stable speech coordination, the higher the ratings. Self reported group competence was significantly predicted by the level of building coordination: the less building coordination, the higher the ratings (cf. Tables 6 and 7 and Figure 6). None of the HR predictors were significantly correlated with experience.

Table 6: Relatedness and Interpersonal Coordination

	ß	SE	p-value
R^2m: 0.45 R^2: 0.45			
HR RR	-69.47	122.03	0.57
HR L	2.69	3.61	0.46
BA RR	-133.05	151.02	0.38
BA L	7.80	3.59	0.03*
SA RR	4.64	13.17	0.73
SA L	-0.28	0.14	0.046*

Table 7: Group Competence and Interpersonal Coordination

	ß	SE	p-value
R^2m: 0.27			
R^2: 0.38			
HR RR	0.93	69.38	0.18
HR L	-1.67	2.04	0.41
BA RR	-0.02	82.12	0.01*
BA L	3.08	2.03	0.13
SA RR	3.08	7.8	0.69
SA L	0	0.09	0.93

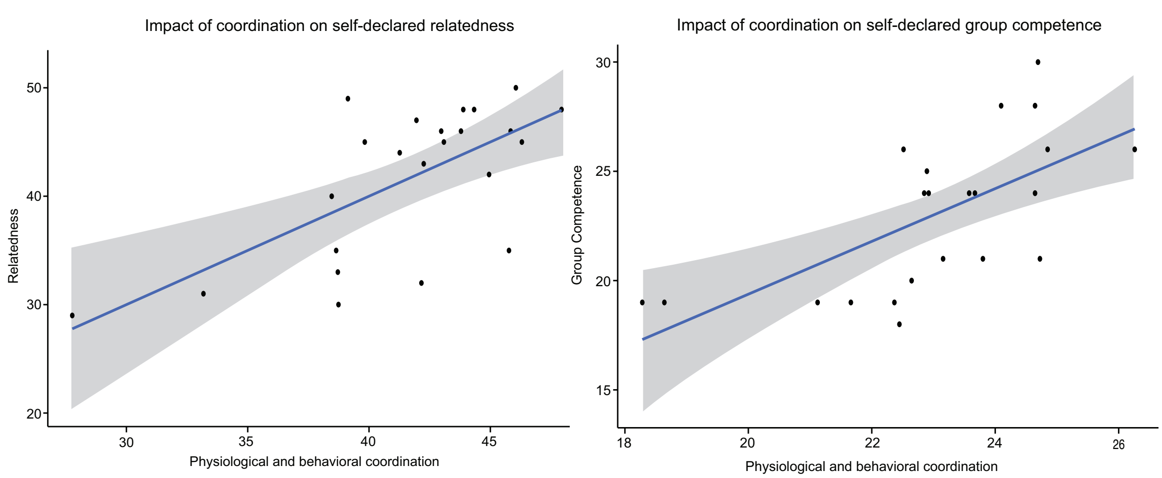

Figure 6: From Interpersonal Coordination to Experience: In the first panel on the left we represent the model predictions against the Relatedness scores. In the second panel on the right we represent the model predictions against the Group Competence scores.

4.3 Discussion

The results suggest that behavioral coordination (building and speech) is a better predictor of the phenomenological experience of group relatedness and competence than HR entrainment. Curiously, HR does not correlate with experience at all. This suggests that in collaborative tasks – in which behavioral coordination is crucial – behavioral coordination mediates both physiological entrainment and experience.

However, it should be noted that the connection between behavioral coordination and experience is not a trivial one: some of the indexes of interpersonal behavioral coordination are negatively related to experience. We speculate that this reflect the complexity of the coordination involved in the creative construction tasks. While most studies reporting only positive correlations between coordination and experience focus on participants performing similar actions, our task affords complementary behavioral dynamics: as good routines and social roles are established within the groups, participants might distribute their engagement with one person doing most of the talking and another building (Bjørndahl et al., in press; Strang et al., 2014; Wallot et al., submitted). Future studies will have to look into the more fine-grained details of speech and motor behaviors to better understand the nature of the coordination being established.

5. General Discussion

Our findings present a nuanced perspective on the complex nature of HR entrainment. Even in a relatively low arousal task, such as LEGO construction tasks, we find reliable entrainment of heart rates between collaborating individuals. A number of factors seem to impact the level and structure of HR entrainment. HR entrainment can be shown to vary according to the demands of the task: individual trials induce higher level of HR entrainment than collective trials. We speculate that this is because in individual tasks, participants do the same (quietly build each their model). However, only collective trials show the marks of actual interactions: within-group pairs display a significantly higher stability of HR entrainment than virtual pairs in collective, but not in individual trials. Similarly, HR entrainment grows during collective, but not during individual trials. Further supporting this line of arguments, HR entrainment during collective trials was predicted by level and stability of speech and building coordination: the more behavioral coordination, the more HR entrainment. Consistently, we observed behavioral coordination (but not HR entrainment) to predict perceived group relatedness and competence.

Our findings both articulate and challenge previous findings in the literature on HR entrainment. They corroborate the hypothesis that collective settings involve HR entrainment, and articulate two separate aspects of entrainment – level and stability -, but they also question its potential role as foundational mechanism for shared experience, rapport and collective performance.

HR entrainment can be argued to rely on several interacting factors. For instance, the structure of the task – e.g. having to build a LEGO model – seems to drive the level of HR entrainment as it impacts and constrains the general amount of engagement and physiological arousal in participating individuals. However, the fine-grained dynamics of entrainment seems to be related to the actual unfolding and development of interpersonal behavioral coordination. Indeed, behavioral coordination is a weak predictor of the amount of HR entrainment (Building RR) and a strong predictor of its structure (Speech RR and L). The collective LEGO construction task requires participants to develop coordinative strategies at many levels: negotiating concepts, taking turns in speaking and in building the models (Bjørndahl et al., 2014, in press). By developing shared behavioral routines, jointly regulating the group's action and speech (and thus indirectly respiration), the participants become partially entrained even at a physiological level. Interestingly, these behavioral routines, with their complementary roles (A speaks, B listens; A holds the model, B adds a brick) are much more informative about the emotional environment and competence of the groups than their physiological entrainment. In other words, heart rate entrainment does not play a causal role: participants do not need to synchronize their hearts to feel related or coordinate their speech and building actions. However, they might need to coordinate their behavior in systemic ways in order to effectively solve the task at hand and that in turn is reflected in entrainment of their physiological states.

This also suggests that behavioral coordination and physiological entrainment are not a universal panacea, automatically creating shared emotions, empathy and performance. Rather, the structure of the task seem to be a crucial factor in determining which aspects of interpersonal coordination facilitate the development of rapport and collective performance.

Our findings seem to support the interpersonal synergy model of social interactions: i) Defying any attempt at a simplistic explanation, interpersonal coordination is always shaped by its context and goals. ii) Interpersonal coordination takes more complex forms than simply "doing the same thing". iii) Performance and experience of the interactions are plausibly not connected to a universal coordinative mechanism, but to coordinative dynamics that meet the requirements of the task and social activities involved.

Future research will have to compare tasks with different coordinative requirements to investigate additional sources of physiological entrainment and more precisely pinpoint the physiological mechanisms through which behavioral coordination impacts physiological entrainment, and their relation to experience and performance.

6. Conclusion

The findings in our study suggest that physiological entrainment can be found in collective activities and is influenced by a plurality of factors such as structure of the task and the behavioral coordination among interacting individuals. They also point to the fact that physiological entrainment should not be considered the unmediated proxy for shared emotions, empathy and collective performance. Rather behavioral coordination – at least in tasks requiring forms of joint action – seems to be driving both physiological entrainment and collective experience.

Acknowledgments

We would like to thank Ivana Konvalinka, Linda Post, John McGraw, Robert Rasmussen, Bo Stjerne Thomsen, and the LEGO Foundation. The research in this paper was funded by the Danish Council for Independent Research – Humanities grant "Joint Diagrammatical Reasoning"; the ESF EuroUnderstanding grant "Digging for the Roots of Understanding" and the Interacting Minds Centre, Aarhus University.

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