

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. We investigate the presence, temporal development, possible mechanisms and impact of interpersonal heart rate entrainment during collective creative LEGO construction tasks. We observe a statistically significant presence and increase over time of structured entrainment, which relates to the actual unfolding and development of behavioral coordination. Heart rate entrainment does not predict rapport and perceived group competence, but behavioral coordination does. Physiological entrainment, thus, should not be considered a universal unmediated proxy for shared emotions, empathy and collective performance. Behavioral coordination – at least in tasks requiring forms of joint action – seems to be a more informative proxy for both physiological entrainment and collective experience.

Keywords: interpersonal coordination; joint action; common ground; physiological entrainment; behavioral coordination.

Introduction

As we go through our day, we continuously engage with other people: chats at the bus stop, joint projects at the work place, and nurture of long term relations with friends and family. Which processes are involved in the development of such coordination and rapport? Recent studies have investigated the multiple behavioral coordinative dynamics that interacting individuals put to play - from mutual adaptations of movements, words and prosody (Fusaroli et al., 2012; Riley, Richardson, Shockley, & Ramenzoni, 2011; Shockley, Santana, & Fowler, 2003), to establishment of shared routines (Fusaroli, Raczaszek-Leonardi, & Tylén, 2014; Mills, 2014) – and their role in facilitating performance and rapport (Fusaroli & Tylén, in press; Marsh, Richardson, & Schmidt, 2009). Moreover, a small but growing number of studies points to the crucial role of

physiological entrainment, in particular of heart rate (henceforth HR). The study of interpersonal HR entrainment seems promising: it is argued to underlie the construction of a sense of community (Konvalinka et al., 2011), to facilitate empathy and mindreading (Levenson & Gottman, 1983; Levenson & Ruef, 1992) and even to be predictive of team performance (Elkins et al., 2009; Henning, Boucsein, & Gil, 2001; Strang, Funke, Russell, Dukes, & Middendorf, 2014).

However, these initial results open many questions, which are crucial for our understanding of physiological entrainment and its role in social interactions. Since there is no direct coupling between hearts, which factors enable and facilitate HR entrainment? The current literature points to social relationships (Konvalinka, et al., 2011; Levenson & Gottman, 1983), and the structure of task environments (Henning, et al., 2001; Strang, et al., 2014) as important factors. However, social interactions crucially involve behavioral coordination, which could in turn mediate physiological entrainment (Dale, Fusaroli, Duran, & Richardson, 2013; Konvalinka & Roepstorff, 2012). To what extent is HR entrainment modulated by these factors? And how do behavioral and physiological entrainment relate to the more phenomenological aspects of interaction, such as perceived group competence and rapport?

To investigate these questions, we designed an experimental study inspired by the intervention method LEGO Serious Play (Gauntlett, 2007). Groups of participants repeatedly collaborated to build LEGO models illustrating their understanding of six abstract notions. The task thus afforded the development of coordinative routines and strategies: group members could not all build or talk at the same time but had to find ways 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 the presence and temporal development of HR entrainment. In study 2 we investigate the behavioral proxies through which HR entrainment can be established and maintained: in particular we assessed building and speech coordination. In study 3 we then investigated whether physiological and behavioral coordination enable us to predict the experience of the interactions, in particular focusing on experiences of group relatedness and group performance.

Study 1 - Heart Rate Entrainment

In study 1, we investigate whether HR entrainment could be observed during creative collaborative LEGO construction tasks and whether it was driven alone by individual task-engagement, or it developed as behavioral collaboration between group members unfolded. We contrasted HR entrainment in pairs of participants interacting with each other (real pairs) and in pairs artificially constructed by selecting participants from two different groups, thus sharing the task, but not any actual interactions (virtual pairs). Additionally, we assessed the temporal development of HR entrainment across the six construction tasks in both real and virtual pairs.

If HR entrainment is mainly driven by the structure of the task, that is, by similarities in what all individual participants do, real and virtual pairs should not differ. However, if HR entrainment is connected to the development of behavioral coordination between participants, real pairs should display a higher degree of coordination and an increase over time when compared to virtual pairs.

Materials and Methods

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.

Design and Procedure Upon arrival, a heart rate monitor (Polar Team2) was attached to the participants. Participants were placed around a table and familiarized with the task through two practice trials. 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 construction tasks of each five minutes, during which their HR entrainment was measured. In each trial, participants were instructed to use LEGO blocks to construct their understanding of 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 have an opinion about

them but still challenging to construct in LEGOs. In individual trials, participants sat quietly and constructed their own models. In collective tasks participants freely interacted to construct joint models. The experiment was divided in two 3-concepts sessions separated by a 20 min. coffee break. Two cameras were used to video-record the experiment from different angles, leading to approximately 20 hours of videos (for more details on the interactions during such collective tasks, cf. (Bjørndahl, et al., 2014, in press)). Importantly, to answer the research questions put forth in the introduction, we will in the following only consider data from the collective condition.

Heart Rate Activity Polar Team2 (Polar, 2013) chest-strapped HR monitors were used to record participants' cardiac activity as the temporal distance between beats (R-R intervals) with millisecond accuracy. To align HR activity across participants we generated equally sampled time-series by estimating beats per minute every second based on sliding 5-second windows (Wallot, Fusaroli, Tylén, & Jegindø, 2013).

Data Analysis: Interpersonal Physiological Entrainment

Interpersonal entrainment was measured through Cross Recurrence Quantification Analysis (CRQA), a nonlinear and more flexible analog of cross correlation. 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 (for more details on the methods, cf. (Fusaroli, Konvalinka, & Wallot, 2014; Marwan, Carmen Romano, Thiel, & Kurths, 2007). CRQA has been previously used to assess HR entrainment (Konvalinka, et al., 2011; Strang, et al., 2014; Wallot, et al., 2013) and allows us to quantify, amongst other things:

- *Level of entrainment*, 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 entrainment*, 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.

Data Analysis: Surrogate vs. Real Pairs To assess the presence of interpersonal HR entrainment we calculated CRQA indexes in real pairs (two members of the same group) and in surrogate pairs (two members of different groups). All possible pairs within a group were calculated. Per each real pair we randomly selected a participant and paired her with a participant from a different group, thus generating a surrogate pair. This generated 56 real pairs and 56 surrogate ones, measured during each of the 6 collective tasks. Since we excluded HR time series in which the sensor lost contact for more than 5 s, we ended up with a total of 653 data points (out of 672 possible). Both real and surrogate pairs should show presence of task-based

entrainment, but only real pairs should show interaction-based entrainment.

Data Analysis: Assessing the Presence and Temporal Development of Physiological Entrainment In order to assess the presence of entrainment and the impact of the experimental manipulation, we employed mixed effects linear models. Each index of HR entrainment (RR and L) was separately employed as dependent variable, surrogate vs. real, and time were used as fixed effects, pair and group variability were used in a full random effects structure including random slopes for all fixed effects. Notice that the random effects structure constrains the degrees of freedom in the same way as a multi-level repeated measures model.

Results

Presence and Development of Entrainment The stability (but not the level) of entrainment was higher in real pairs than in virtual pairs and shows an interaction between real and time (cf. Figure 1 and Table 1). The interaction is driven by an increase of stability of entrainment in real pairs ($\beta=0.30$, $SE=0.09$), but not in virtual pairs ($\beta=0.03$, $SE=0.08$).¹

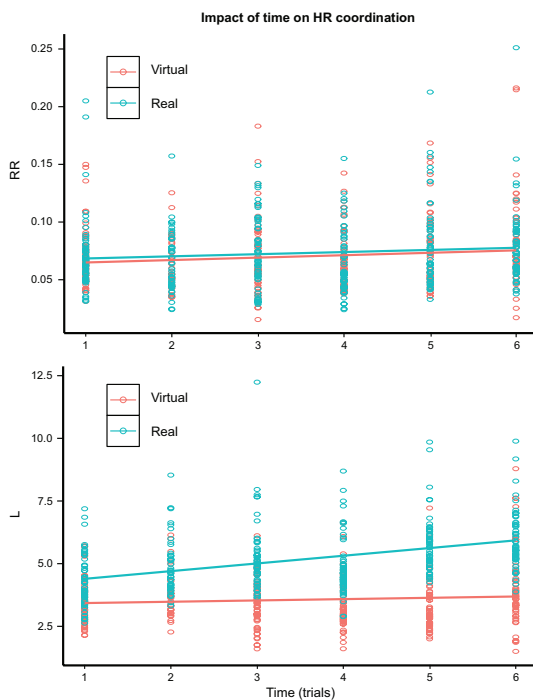


Figure 1: Level (RR) and Stability (L) of interpersonal HR entrainment over time.

Table 1: Presence and Development of HR Entrainment

Variable	Factor	β	SE	p-value
RR	Real	≈ 0	≈ 0	0.45
	Time	≈ 0	≈ 0	0.008*
$R^2_m=0.03$				

¹ Analogous results were achieved when controlling for order of condition and session effects.

$R^2=0.16$	Real*Time	≈ 0	≈ 0	0.96
L	Real	0.64	0.2	0.002*
$R^2_m=0.38$	Time	0.17	0.11	0.11
$R^2=0.51$	Real*Time	0.12	0.05	<0.0001*

Discussion

The results suggest that HR entrainment can indeed be found during creative collaborative construction tasks and that it is at least partially the effect of actual interactions and not just individual task-constraints. Indeed, if HR entrainment was driven by presence in an analogous context performing an analogous activity, real and virtual pairs should not differ in their average level of entrainment and development over time.

However, this is only true for the structure (L) and not the level (RR) of HR entrainment suggesting that collaborative tasks involve not just shared engagement (generally being equally physiologically aroused), but repeated, prolonged sequences of entrained physiology.

Study 2: From behavioral coordination to physiological entrainment

Study 1 supported the hypothesis that HR entrainment is related to actual interpersonal interaction during the collective construction tasks. This raises the issue of which aspects of the interactions facilitate HR entrainment. The collective construction of LEGO models requires at least two aspects of behavioral coordination: participants have to discuss and agree upon their joint project, which requires taking turns in dialogical interaction; participants have to physically build the model and coordinate their actions, as they cannot all manipulate the model at the same time. As both motor and speech activity have been related to HR activity (Beda, Jandre, Phillips, Giannella Neto, & Simpson, 2007; Wallot, et al., 2013), we hypothesized that their coordination might impact HR entrainment. In order to pursue this hypothesis, Study 2 quantified building and speech activity (BA and SA) coordination and assessed their relation to HR entrainment.

Materials and Methods

Speech and Building Coding In order to investigate the potential mechanisms enabling HR entrainment we quantified speech and building coordination. Two research assistants naive to the purpose of the study carefully screened the videos of the collective tasks and coded for presence/absence of speech and/or building activity for each participant on a second-by-second base.

Speech and Building Coordination Speech and building interpersonal coordination were calculated using CRQA on the nominal (1s and 0s) time series of speech and building activity in real pairs during collective tasks (Dale, Warlaumont, & Richardson, 2011). CRQA allows us to quantify the level (RR) and structure (L) of behavioral coordination, in terms of shared engagement (RR) and

stable patterns of coordination (L), beyond simple behavioral synchrony – e.g. including stable patterns of turn-taking. 56 real pairs assessed during 6 collective trials generated 320 data points (16 had to be excluded due to corrupted audio-video materials).

Data Analysis: Assessing the Relation of Behavioral Coordination on HR entrainment In order to assess the potential impact of behavioral coordination on physiological entrainment we employed a mixed effects linear model with each of the indexes of HR entrainment (RR and L) as dependent variable, all 4 indexes of speech and building coordination as fixed factors and a random intercepts for group and pair variability (as models with random slopes would not converge).

Results

The level of HR entrainment (HR RR) was significantly related to the level of building (Build RR) and the stability of speech (Speech L) coordination: the more frequent the building and the more stable the speech coordination the more HR entrainment. The stability of HR entrainment was significantly related to speech coordination: the more frequent and stable the speech coordination, the more HR entrainment (cf. Table 2 and Figures 2&3).

Table 2: From Behavioral to Physiological Coordination

Variable	Factor	β	SE	p-value
HR RR $R^2_m=0.14$ $R^2=0.23$	Build RR	0.23	0.12	0.045*
	Build L	≈ 0	≈ 0	0.248
	Speech RR	0.01	0.01	0.456
	Speech L	≈ 0	≈ 0	0.0013*
HR L $R^2_m=0.37$ $R^2=0.47$	Build RR	2.04	4.19	0.63
	Build L	-0.16	0.09	0.077
	Speech RR	1.77	0.45	<0.0001*
	Speech L	0.02	≈ 0	<0.0001*

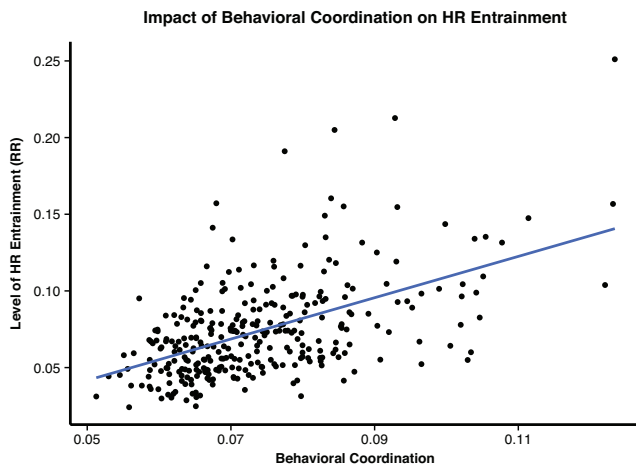


Figure 2: From Behavioral Coordination to Physiological Entrainment: model predictions against the real HR RR scores.

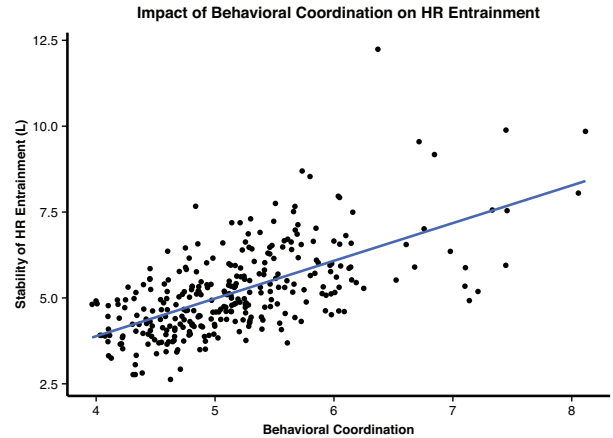


Figure 3: From Behavioral Coordination to Physiological Entrainment: model predictions against the real HR L scores.

Discussion

The results support the hypothesis that HR entrainment is connected to – and possibly partially driven by - behavioral coordination. Speech Coordination significantly and noteworthy predicts the stability of HR entrainment (37% of the variance explained). Building coordination significantly, but more weakly predicts the level of HR entrainment (14% of the variance). Given that study 1 pointed to no role for actual interactions in determining the level of entrainment, this is not surprising. In any case, Building and Speech coordination seem to contribute in complementary ways to HR entrainment.

Study 3 – Coordination, Entrainment and Experience

Study 2 supported the hypothesis that HR entrainment is – at least partially – driven by behavioral coordination. In previous studies, behavioral coordination and HR entrainment have both (although separately) been related to the phenomenological experience of social interactions (Konvalinka, et al., 2011; Marsh, et al., 2009). In Study 3 we explore the relation between self-declared group relatedness and competence in the task and the different indexes of interpersonal coordination and physiological entrainment.

Materials and Methods

Experience of the Collaboration In order to provide insight on 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 rephrased to better capture: i) *Relatedness to the group* and ii) *Perceived collective competence*.

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.

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 3 and 4).

Table 3: Relatedness and Interpersonal Coordination

	Beta	SE	p-value
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 4: Group Competence and Interpersonal Coordination

	Beta	SE	p-value
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

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 (which indeed does not significantly correlate with experience at all). This seems to point to behavioral coordination underlying both physiological entrainment and experience. Both behavioral modalities seem to play a role in creating coordinative routines and experience. However, their role is not straightforward as higher indexes of interpersonal coordination might have a negative impact on the experience.

General Discussion

Our findings support and articulate the current literature on HR entrainment. They corroborate the hypothesis that collective settings involve HR entrainment, 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 the participating individuals. However, the fine-grained structure of the entrainment seems to be related to the actual unfolding and development of 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). As the possible drive of physiological entrainment, it might not be surprising that behavioral coordination - and not physiological entrainment - relates to experience.

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. However, it seems to be the behavioral routines, with their complementary roles (A speaks, B listens; A holds the model, B adds a brick), rather than the physiological entrainment, which are crucial to effectively solve the task and create a constructive emotional environment where participants feel related and competent in what they are doing. In other words, participants do not need to synchronize their hearts to feel related, but they might need to coordinate their behavior in systemic ways in order to effectively solve the task at hand. However, the negative relation between coordination and experience requires further studies.

The findings thus suggest that behavioral coordination and physiological entrainment are not a universal panacea, automatically creating shared emotions, empathy and performance. On the contrary, the structure of the task at hand might play a crucial role in determining which aspects of interpersonal coordination facilitate the development of rapport and collective performance.

Future research will have to compare tasks with different coordinative requirements and to more precisely pinpoint the physiological mechanisms through which behavioral coordination impacts physiological entrainment.

Conclusion

The findings in our study suggest that physiological entrainment can be found in collective activities and is influenced by a plurality of factors. However, physiological entrainment should not be considered the unmediated proxy for shared emotions, empathy and collective performance.

Behavioral coordination – at least in tasks requiring forms of joint action – seems to be driving in complex ways both physiological entrainment and collective experience.

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