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Physiological evidence of interpersonal dynamics in a cooperative production task

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Abstract

Recent research suggests that shared behavioral dynamics during interpersonal interaction are indicative of subjective and objective outcomes of the interaction, such as feelings of rapport and success of performance. The role of shared physiological dynamics to quantify interpersonal interaction, however, has received comparativley little attention. In the present study, we investigate the coordination dynamics of multiple psychophysiological measures and their utility in capturing emotional dynamics in teams. We use data from an experiment where teams of three people built origami boats together in an assembly-line manner while their heart rate, skin conductance, and facial muscle activity were recorded. Our results show that physiological synchrony of skin conductance measures and eletromyographic measures of the corrugator supercilii develops spontaneously among team members during this cooperative production task. Moreover, high team synchrony is found indicative of team cohesion, while low team synchrony is found indicative of a teams' decision to adopt a new behavior across multiple production sessions. We conclude that team-level measures of synchrony offer new and complementary information compared to measures of individual levels of physiological activity.

Keywords: Interpersonal dynamics, Psychophysiology, Synchrony, Recurrence Quantification Analysis.

1. Introduction

Many theoretical accounts of interpersonal emotions emphasize interactions, processes and dynamics [1-3]. Interestingly however these interactions, processes and dynamical aspects of team emotions are relatively neglected in empirical studies. Empirical studies often measure team emotions as state concepts, for instance as convergence of self-reported or observer-rated mood [4], or emotional contagion [5]. Our focus is on the dynamics that happen as a team is engaged in team work, so the relevant time-scale is

seconds, minutes and perhaps hours rather than days, weeks or months. While variation in team mood over longer time-scales has been investigated in longitudinal studies [6, 7] such long-term variation can be neglected at short time-scales and be considered a stable underlying state on top of which the shorter time-scale dynamics play out. A notable early study that investigated affective changes at short time-scales is Gottman and Levenson [8] who pioneered a method to study the dynamics of affective interactions using both self-report and physiological measures, but at the time the methods to properly quantify such effects had not yet been developed.

This gap between theoretical accounts that emphasize dynamics and the scarcity of empirical evidence seems unsatisfactory and may hinder progress in research and understanding of team emotions. As long as theories of team emotions incorporating dynamic aspects are only partially tested by empirical studies, we are left to infer the dynamic aspects of emotional interactions from static evidence, even though they may be evident to the observer, and can be described qualitatively. To capture emotional dynamics, we need to include measures of time dependent aspects of emotions.

Two challenges appear when aiming to measure and analyze team emotions in a way that takes the dynamics into account. The first challenge is to obtain measures of emotions that are sufficiently frequently sampled or even continuous, so that we have data that retain the dynamics. The second challenge is to analyze the data in a way that captures the team processes, i.e., how emotions change over time and how these changes are related between members of a team.

Inspired by the latest research on team interaction from psychology and biology [9-12], we suggest a way to theoretically conceptualize the dynamics of team emotions that can be used to analyze continuous measures of emotion. More specifically, we suggest that the first challenge – measurement frequency – can be addressed by employing physiological

measures, as opposed to self-reports. Psychophysiological measures of emotion are sufficiently unobtrusive that they can be used in teams, and at the same time they are ideally suited to capture the emotional dynamics that occur in teams on time scales as short as minutes or even seconds. Further, physiological responses are robust indicators of autonomic nervous system activity that is related to emotion, e.g., heart rate, skin conductance, pupillary dilation, and facial electromyography [13-16]. We suggest that the second challenge – team-level analysis of continuous data – can be addressed by looking at the co-evolution of these physiological measures between members of a team. Cross-Recurrence Quantification Analysis (CRQA) is a nonlinear analysis technique that quantifies the coupling between two signals, and that has been widely used to quantify behavioral and physiological dynamics in interpersonal settings [10]. In that sense, CRQA provides measures of synchrony between interactants.

Synchrony of involuntary and automatic physiological responses such as heart rate, skin conductance, respiration and facial expressions have been demonstrated to occur across a wide range of different contexts and measures. For instance, Levenson and Gottman [8, 17] found evidence for synchrony between spouses engaged in conversation and Chatel-Goldman et al. [18] observed that touch increases skin conductance synchrony in couples. Konvalinka et al. [9] found that persons performing a religious firewalking ritual had higher heart rate synchrony with related spectators than with unrelated spectators. In the same vein, Mitkidis et al. [19] showed that high degrees of heart-rate synchrony in an unrelated joint task was predictive of high mutual trust, expressed in terms of a public goods game.

These studies show that physiological synchrony can develop spontaneously, presumably as a consequence of emotional contagion. The studies also show that *physiological* synchrony in closely related participants develops even in the absence of *behavioral* synchrony. This is a strong indication of the relevance of these patterns of

synchrony in the study of emotional interactions. Controlled laboratory studies have shown that mimicry and synchronization of behavior leads to prosocial behavior [20], increased cooperation [11, 12], increased affiliation [21], and rapport [22]. The research summarized above leaves open two important questions, that we will examine in this paper: i) Does physiological synchrony develop in newly formed teams of unrelated participants in the absence of behavioral synchrony? ii) Is physiological synchrony associated with perceptions of affiliation, and better cooperation? In this paper we examine whether team members display above chance physiological synchrony, and—if so—whether team members who display high physiological synchrony perceive the cooperation as running more smoothly than team members who are less synchronous.

To examine these questions, we reanalyze data from a previous laboratory study by Håkonsson et al. [23] in which teams of three persons worked on an interdependent, sequential task (folding specific origami models). The measures used in the study were heart rate (from electrocardiogram), electrodermal activity, and facial electromyography of zygomaticus major and corrugator supercilii, which are all widely used psychophysiological indicators of emotion [13, 24-27]. The main finding in [23]was that declines in performance increased the probability that teams would adopt a new routine. They also found a marginal positive effect of positive emotions on team decisions to adopt a new routine, i.e., both average valence from self-report data and average level of zygomaticus major activity recorded at the beginning of the experiment had a positive relation to the team's adoption of a new routine. Further, they found that teams successful at implementing new routines reported increased positive emotions, as measured by the self-report data. This relationship was fully mediated by performance.

1.1. Hypotheses

We will analyze the data from the previous experiment [23] to test our two main hypotheses: i) that pairs of people from the same team (true dyads) have higher synchrony than pairs of people taken from different teams (pseudo dyads); and ii) that synchrony is positively correlated with the perceived quality of cooperation and liking. Furthermore, since the previous experiment included a team decision, we will iii) explore whether team members who display high synchrony are more or less willing to adopt a new routine than those who are less synchronous. However, since we are looking at synchrony, we can only study such decisions at the dyad level, and therefore cannot directly compare our results to the study by Håkonsson et al. [23].

2. The present study

The data for our analyses come from the study by Håkonsson et al. [23], who adapted an experimental task from Kane, Argote, and Levine [28]. In the experiment, team members were required to construct as many origami sailboats as possible during five four-minute production periods. During the initial instruction phase, positive or negative emotions were induced. The emotional induction was achieved by the experimenters following the facial, vocal, and postural instructions to induce different emotions developed by Bartel and Saavedra [4]. This induction method has been used successfully before [5], and was deemed effective due to its ecological validity. Inducing emotions via interactions with an experimenter is appropriate when the purpose of a given study is to examine interpersonal, rather than intrapersonal effects. Further, an indirect and subtle induction was argued to be more realistic to represent strategic decision making in "real-life" situations. After the instruction phase, teams started the actual work process. The origami construction task was divided into three roles, with each team member performing one of three roles in a sequentially interdependent task similar to a production line. Each team member was

assigned to the same role throughout the experiment. After completing production period number three, all teams were presented with an alternative routine of how to construct the origami sailboats and given the choice to either adopt this new routine for the next production period (number four), or to continue with the old routine. After completing production period number four, all teams were again given the choice to switch routines or continue with their current routine. Throughout all five production periods, physiological measures of heart rate, skin conductance, and facial muscle activity were recorded.

3. Method

3.1. Participants

The participants were 153 students (78 male, 75 female) from Aarhus University ranging in age from 18 to 58 years old (μ=24.0, σ=4.5) who were paid 214 DKK[2] (approximately 36 USD) to participate. The study was run using same-gender teams, and within each gender the participants were randomly assigned to the experimental conditions. The two experimental conditions were positive/active in which participants were induced by a trained experimenter acting positive (valence) and active (arousal); and negative/inactive in which the experimenter acted negative (valence) and inactive (arousal). The conditions were chosen in this manner to maximize the difference between the two conditions. The emotional induction followed the procedure used, e.g., by Barsade [5] that builds on the protocols developed by Bartel and Saavedra [4]. In the positive/active condition the experimenter would frequently smile, speak fast in a strong voice and maintain eye contact with the

[2] This amount was chosen because it is equivalent to two hours of salary for a student assistant.

participants, whereas in the negative/inactive condition the experimenter would not smile at all, speak slowly in a low voice and avoid eye contact with the participants.

3.2. Procedure

On each day of the experiment three teams were in the lab to perform the origami sailboat construction task. The participants were told that the team which produced the most origami sailboats on a particular day would win a prize of 150 DKK. Teams thus had an incentive to make as many boats as possible, but did not have the opportunity to monitor other teams' performance.

An overview of the experimental procedure is shown in Figure 1. After participants had been assigned to their respective roles in the production task they were seated next to each other at a table in the order dictated by their sequential roles. Electrodes were then attached to the participants to enable recording of the psychophysiological data (labeled 'participant preparation' in Figure 1).

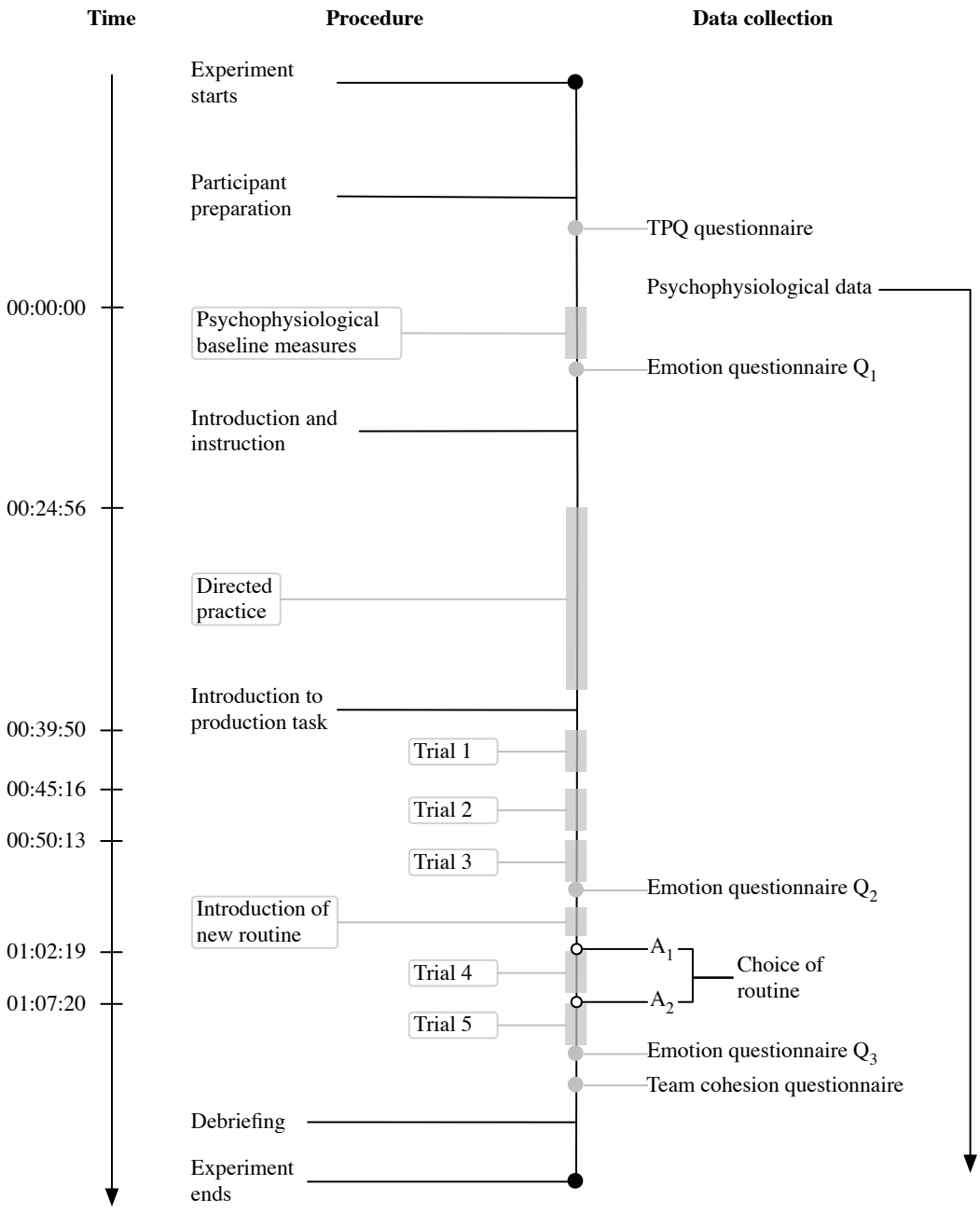

Figure 1. Overview of experimental procedure. The experiment starts at the top and ends at the bottom. A_1 and A_2 indicate the two points at which the teams had an option to adopt the new routine. The timing of events (average over all groups) is shown at the far left. TPQ, Q_1, Q_2, and Q_3 indicate when questionnaires were filled out. Unlike the team cohesion questionnaire, the data from these other questionnaires are not used in the present study, but are reported on in [23].

The participants were then instructed to sit as quietly as possible during a five-minute baseline measurement. Before the actual production periods the participants received general instructions about the task ('introduction and instruction' in Figure 1) and then received training in how to produce a particular origami sailboat (directed practice). After a brief description of the production task, they proceeded to produce origami sailbots for three consecutive four-minute production periods (trial 1–3) during which they were not allowed to talk to each other. During each trial the participants would construct as many origami boats as possible. They were assigned separate roles in the construction, such that one team member would perform the initial folds and then pass the folded origami paper on to the next team member who would perform the next folds, after which the third team member would perform the last folds to finish the origami sailboat. The participants were not allowed to talk to each other during the trials, and they were not allowed to perform folds not assigned to their own role. Only finished boats counted toward the total score (1 point), and there was a small penalty (0.1 point) for folded paper that was not turned into a completed boat. The origami folding task was adapted from the task used in [28]. After trial three they were told that the research and development department had developed a new boat that meets product specifications, but may be faster to produce. They were shown a video with a same-gender person instructing them how to make this new boat, but were not allowed to practice the new boat. For the following production period (trial 4) they were told that they could decide which of the two boats they would make, but they could only make one type of boat during each production period. They had the same choice before production period five, and after this last production period they were told that the sixth production period would be cancelled due to lack of time. This design was chosen to avoid effects of participants knowing that the fifth period would be the last.

3.3. Measures

The recorded psychophysiological measures were electrocardiogram (ECG), skin conductance or electrodermal activity (EDA) and two measures of electromyography (EMG); one for zygomaticus major (smile) and one for corrugator supercilii (frown). These measures were chosen for two reasons: In the original study, we were interested in capturing physiological correlates of arousal (skin conductance and heart rate) and valence (zygomaticus major and currogator supercilii EMG) as two main components of affect [29, 30]. Multiple measures of each of these two components were chosen because this allowed for a more detailed description of the social-affective interactions (i.e., capturing frowning and smiling allowed us to distinguish between the presence of either positive of negative emotional valence, while capturing only smiling would only have revealed the presence of positive display of emotions). Moreover, single physiological measures do not always reliably capture emotional states, and a combination of multiple measures is sometimes needed [31, 32].

At the end of the experiment the participants filled out a team cohesion questionnaire that contained questions relating to group belonging and how the cooperation was perceived. In addition to physiological measures and questionnaire data, the experimental session was recorded on video and the number and quality of the boats produced in each production period as well the teams' choice of routine in period four and five (A_1 and A_2 in Figure 1) were recorded.

3.4. Data acquisition

A BIOPAC MP150 system with amplifiers for EDA (GSR100C), ECG (ECG100C) and EMG (EMG100C) was used to simultaneously record physiological data from all three

participants[3]. Since participants needed both hands free for the experimental task EDA signals were recorded with electrodes (BIOPAC EL507 electrodes pre-gelled with isotonic gel) placed on the pantar surface of one of each participant's feet, which is recommended as an alternative to planar measurements [33, 34]. The negative electrode also provided grounding for the ECG and EMG measurements on the same participant. ECG was recorded with BIOPAC EL504 reusable electrodes with Ag/AgCl gel. One electrode was attached on each side of the participants' thorax at the height of the lower sternum. EMG was recorded using BIOPAC EL254S 4 mm reusable electrodes with adhesive disks and gel. One pair of electrodes was attached to each participant's cheek (zygomaticus major) and one pair was attached to the brow (corrugator supercilii) according to the guidelines provided by Fridlund and Cacioppo [35]. Data were recorded with the BIOPAC MP150 system, using an LED to synchronize the data time with the time code in a video camera used to record the experimental session. Research assistants later used the video recordings to code all relevant experimental events using this common time base.

3.5. Data preprocessing

The ECG signals for the three participants in each group were recorded simultaneously and digitized at 1 kHz. The ECG data were subsequently band-pass filtered between 0.5 Hz and 25 Hz to remove noise, and inspected for artifacts. The filtered ECG signal was converted to a heart rate signal by the built-in rate detection algorithm in BIOPAC Acqknowledge 4. The skin conductance signals were digitized at a sampling rate of 125 Hz with the GSR100C electrodermal amplifier working in DC mode with the low-pass filter set to 1 Hz. A phasic EDA signal was computed from the tonic signal recorded by using the built-in algorithm in

[3]BIOPAC guidelines for multiple subjects were followed to avoid ground loops, and only one ground electrode was used per participant.

BIOPAC Acqknowledge 4 based on a 0.05 Hz high-pass filter. The electromyographic signals were recorded and digitized at 125 Hz with the EMG100C amplifier set to perform an analog band-pass filtering between 100 Hz and 500 Hz. The 100 Hz high-pass filter served to filter out artifacts (e.g. from eye movements) [35, 36] and the 500 Hz low-pass filter is an antialiasing filter. EMG signals have both positive and negative values, so the mean was substracted from each signal to give a centered signal before full-rectification. The rectified EMG signal was then smoothed using a moving average filter with a time interval of 0.5 s. All signals were downsampled to 3.90625 Hz (1 kHz/256 = 125 Hz/32 = 3.90625 Hz) to give a manageable data rate for the subsequent analyses.

Sampling the EMG data at 125 Hz rather than 1 kHz was due to an error in the template used as a basis for recording all experimental sesssions. The error was not spotted until after all data were recorded, and could therefore not be corrected. This means that the EMG data are under sampled relative to the standard guideline sampling rate of 1 kHz [37]. In particular this means that the antialiasing filter did not serve its intended purpose. This would present a problem if we were interested in analyzing the spectral distribution of the EMG signals, but since we are only interested in the smoothed moving average of the signal, we rely on results showing that smoothed surface EMG signals sampled well below the Nyquist limit are almost identical to those sampled at or above the Nyquist sampling rate [38]. Another reason that the undersampling does not leave us with unusable data is that the signal we are interested in (the smooth outline that results from the moving average) is time domain encoded rather than frequency domain encoded. For a frequency domain encoded signal, the aliasing would be catastrophic, whereas it is much less harmful for a signal whose information is carried in the time domain. While a moving average is considered the worst filter for a frequency domain encoded signal, it is the best for a time domain encoded signal, where it can reduce random noise and retains a sharp step response [39: p. 277]. The

important part of the signal for the purpose of our study is the amplitude at a given point in time, not the frequency components of the signal; hence the step response is important, and the frequency response is not.

3.6. Cross-recurrence quantification analysis

The physiological measures in our study exhibited heterogeneous fluctuation patterns and the resulting time-series are not stationary. Moreover, it cannot be expected that synchrony in the physiological measures will have a constant time-delay, or that any two time-series will always be "in sync." To account for the complex properties of the physiological signals, we use Cross-Recurrence Quantification Analysis (CRQA) to estimate synchrony between two time-series, which can also be used for nonstationary data [40, 41] and has been employed as an analysis technique to quantify synchrony in behavioral and physiological data [10]. The application of CRQA to our data is described in detail in Supplement 1.

The basis for CRQA is a cross recurrence plot, which is a graphical representation that reveals to what degree two time-series exhibit similar patterns over time. Figure 2 shows examples of cross recurrence plots of all three dyads in one of the groups. The data for person A and person B are shown in standard scores in the top left panel, and the resulting cross recurrence plot is shown in the top right panel. Each black dot in the cross recurrence plot corresponds to a pair of time values (t_A, t_B) where the curves exhibit similar values. Requiring exactly the same values will give an empty plot when the variables are continuous. Hence a small tolerance has to be set, so that a difference less than this tolerance is counted as a recurrence. In Figure 2 this tolerance was set to 0.1. The blue lines in the cross recurrence plots indicate the start of the five minute psychophysiological baseline period. Receiving the instruction about this from the experimenter is likely the reason for the sudden increase in skin conductance, followed by the slow decrease as the participants start to relax.

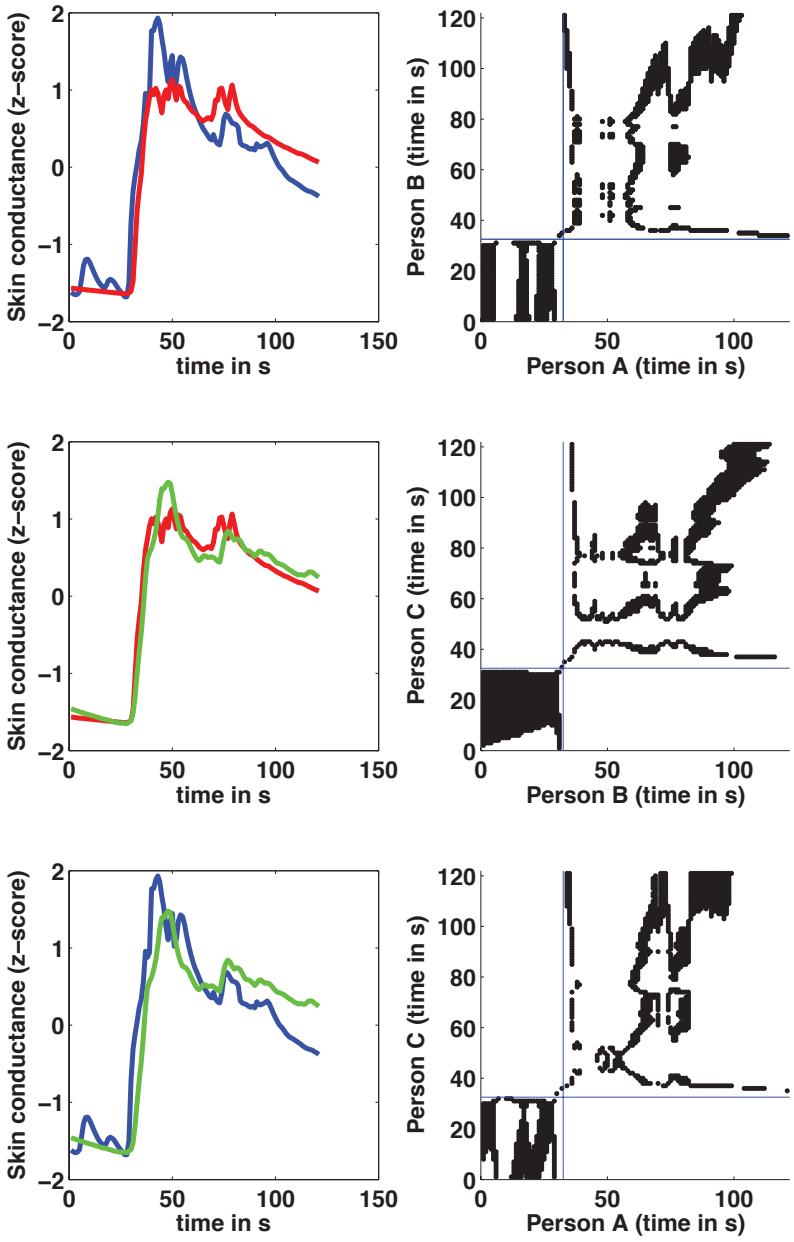

Figure 2. Example skin conductance data normalized as standard scores (left) and the resulting cross recurrence plots (right) for each possible combination of two persons AB (top), BC (middle), and AC (bottom). Each dot in the cross recurrence plot represents a set of times where the two persons had the same value (within 0.1 tolerance) for their normalized skin conductance. The blue lines indicate the onset of the baseline period.

If there is a cross recurrence at (t_A, t_B) and again at the next measurement $(t_A + \Delta t, t_B + \Delta t)$ this will produce two dots lying on a line with a 45 degree angle relative to the axes. If the two time series keep evolving "in synch" one will observe longer diagonal lines in the cross recurrence plot. This is observed in Figure 2 (top panel) from around 80 seconds in both time series, giving rise to "islands" of diagonal structures in the recurrence plot. Note that the other two dyads (BC and AC) give very similar results.

Rather than relying on visual inspection of recurrence plots Zbilut and Webber [42] introduced quantitative measures that characterize the structures in a (cross-)recurrence plot. Commonly used CRQA measures employed to capture synchrony are the ratio of recurrence points in diagonal lines to all recurrence points (determinism, DET); the average diagonal line length (ADL), and the longest diagonal line length (LDL). We focus on these three measures, as they have shown to capture synchronous behavior in oscillator systems [43] and have been applied to measure synchrony in human physiological and behavioral data [10].

Before these measures can be calculated, a few parameters need to be chosen in order to properly represent the dynamics of the time-series. This is done by the method of time-delayed embedding [44, 45]. To embed a time series, the time delay for embedding (τ) and the number of embedding dimensions (m) need to be estimated. Furthermore, a normalization procedure needs to be chosen in order to ensure that the cross-recurrence measures of synchrony are primarily driven by the sequential order in a time-series, and are not biased by simple differences in the absolute magnitude of the values. Finally, because physiological signals are noisy and contain interindividual differences in the physiological response, a radius parameter ε needs to be set in order to define which values are counted as recurrent and which are not. To estimate the parameters, we used the average mutual information function to estimate the time-delay τ and the false-nearest neighbor function to

estimate the dimensionality m for each data set [46, 47]. As a criterion, we chose the first local minimum in each function as the estimate for the parameters and then used the average of those estimates across all participants. As the different physiological measurements exhibit potentially different dynamics or evolve at different time-scales, we repeated this procedure separately for each measure (i.e., heart rate, skin conductance, and electromyography). The Euclidean norm was used to calculate the distance between points in m-dimensional state space. Because inter-individual variation in the physiological measures was substantial, we set the radius parameter ε to yield an average recurrence of at about ten percent to ensure a minimum level or recurrence in order to calculate the CRQA variables. Average recurrence was 10.46% for pEDA, 11.97% for HR, 11.93% for EMG ZM, and 9.60% for EMG CS. Before subjecting the time-series data to the parameter estimation procedures and subsequent analysis, each time-series was downsampled by a factor of two to 1.9531 Hz.

The resulting parameter values values are shown in Table 1 for phasic electrodermal activity (pEDA), heart rate (HR), and the electromyographic measures of zygomaticus major (EMG ZM) and corrugator supercilii (EMG CS). Note that the time delay, τ, is per convention a vector index and therefore dimensionless. The time delay in physical units is obtained, by dividing τ by the sampling rate. Cross recurrence quantification analysis was performed using Marwan's [40] Cross Recurrence Plot Toolbox (v. 5.17).

Table 1

Embedding parameters used at 1.9531 Hz. Embedding dimension *m*, time delay τ, and radius ε

Modality	***m***	***τ***	***ε***
pEDA	5	6	0.66
HR	6	7	1.31
EMG ZM	6	7	0.69
EMG CS	5	6	0.76

3.7. Data analysis strategy

Our goal is to investigate how interpersonal coordination is reflected in physiological measures, and how this coordination in turn is related to subjective perception and performance during the team task. Hence, we first need to assess which of the physiological measures (i.e., skin conductance, heart rate, EMG of zygomaticus major, and EMG of corrugator supercilii) actually exhibit significant traces of interpersonal synchrony above chance. This will be done in the results section 4.1, using a false-pair surrogate analysis. Subsequent analyses will be based on those signals that showed significant interpersonal synchrony only.

Furthermore, CRQA provides several indices that capture aspects of synchronization in the physiological data (DET, ADL, LDL). Hence, in a second step we will employ principal component analysis (PCA) to reduce the dimensionality of the CRQA measures, which has been suggested as a viable solution to reduce data complexity when using conceptually related and highly correlated CRQA measures [48, 49]. Also, the questionnaire data collected consisted of multiple questions related to subjective aspects of social relations among team members and perceived team performance, and will be reduced to a more manageable set of variables via PCA as well. The PCA results will be described in more detail in results section 4.2.

Finally, we will use the thus selected and reduced data to investigate the relation between physiological coordination, subjective perception, group decisions and performance using Pearson correlation, ANOVA and logistic regression in the results sections 4.3 and 4.4.

4. Results

4.1. Synchrony in physiological data

In order to test whether synchrony between members of the same team is higher than synchrony between people coming from different teams, we follow Bernieri et al. [50] in using pseudo-interactions as a control group for the true interactions. Since we are using CRQA to analyze the data, the unit of analysis will be dyads of which there are three in each team of three persons. In order to avoid confounding factors to the greatest possible extent we define pseudo dyads to consist of two persons who were not part of the same team, and therefore did not interact, but who were of the same gender, participated at the same time of day, in the same experimental condition, and who belonged to teams with the same team choice profile ((A_1, A_2) in Figure 1). We refer to synchrony of pseudo dyads as pseudosynchrony, and—using this terminology—testing whether synchrony (of true dyads) is higher than pseudosynchrony is equivalent to testing our first hypothesis that pairs of people from the same team (true dyads) have higher synchrony than pairs from different teams (pseudo dyads). This type of test has also been used in CRQA analysis of speaker-listener pairs and interpersonal coordination of posture [51, 52]. We test this hypothesis with a one-sided *t*-test, independently for each of the four psychophysiological measures, and using three different diagonal CRQA measures for (pseudo-) synchrony: ADL, LDL, and DET. The *p*-values and measures of effect size for these tests are shown in Table 2. For heart rate and corrugator EMG there is no significant difference between the pseudo dyads and the true dyads, but for skin conductance and zygomaticus EMG there is a significant difference, and synchrony is higher than pseudosynchrony in support of our hypothesis. Figure 3 shows the mean and standard error of the average diagonal line length (ADL) across all dyads and pseudodyads, averaged over all trials.

Table 2

Results of one-sided *t*-tests for synchrony being higher than pseudosynchrony reported as *p*-values and Cohen's *d*. Three diagonal CRQA measures, ADL, LDL, and DET, are included for each physiological data type.

RQA	***HR***		***pEDA***		***EMG ZM***		***EMG CS***	
measure	***p***	***d***	***p***	***d***	***p***	***d***	***p***	***d***
ADL	= .29	0.04	< .001	0.22	< .001	0.23	= 0.70	0.03
LDL	= .14	0.07	< .001	0.17	< .001	0.20	= 0.78	0.05
DET	= .80	0.06	< .001	0.21	< .001	0.28	= 0.63	0.02

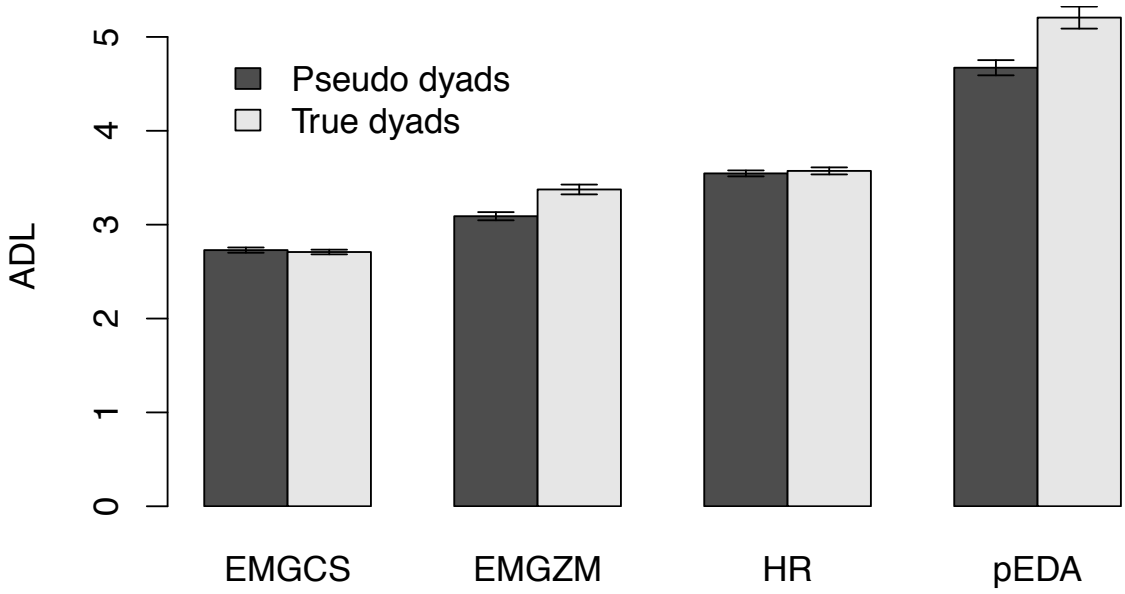

Figure 3. Average diagonal line length (ADL) for true dyads vs. pseudo dyads. The vertical bars indicate the mean ADL over all dyads, and the error bars indicate the standard error of the mean.

Since there was no significant difference between synchrony and pseudo-synchrony for heart rate and corrugator EMG we leave these measures out of the remaining analyses.

4.2. Data reduction

In order to reduce the dimensionality of our data before further analysis, we employed PCA using varimax-rotation on the three CRQA measures DET, ADL, and LDL separately for zygomaticus EMG and skin conductance to derive a single synchrony-score for these variables. Table 3 presents the results of the PCA for these measures, each resulting in a single factor for zygomaticus EMG and skin conductance, respectively. As can be seen from the factors loadings, the three measures are highly redundant in our case, which seems to justify their factorization.

Table 3

Component Matrices for the principle components of synchrony measures for zygomaticus activity and skin conductance

Variables	EMGZM Synchrony Component Loadings	pEDA Synchrony Component Loadings
DET	.889	.922
ADL	.952	.943
LDL	.951	.928
Total Variance Explained	86.69%	86.67%

Note: Only one component was extracted for each modality (zygomaticus activity and skin conductance), as the Eigenvalues for the second components were considerable below one.

The PCA of the 19 questionnaire items resulted in a factor solution that showed substantial cross-loadings, where some of the items loaded positively on more than one factor. Hence, we eliminated these items and ran PCA on the remaining items in order to get a more clear-cut factorial solution. Table 4 presents the results of this resulting in a 3-factor solution. In order to interpret the factors, we took into consideration only substantial factor loading of 0.4 or higher. This suggested that the three factors can be interpreted as follows: Factor 1 showed high loadings on items related to relationship orientation and the expression

of positive affect towards the other group members. Factor 2 showed high loadings on items related to tension in the group and the expression of negative affect towards the other group members. Factor 3 showed high loadings on questions related coordination toward task orientation and performance.

Table 4

Component Matrices for the principle components of the 19 questionnaire items of the team cohesion questionnaire adapted from [28]. Factor loadings of > 0.4 were considered as substantial contributions to a factor and were the basis for interpreting the extracted factors.

Items	Extracted Factors		
	1	2	3
I liked the other participants in the group.	**.832**	-.167	-.129
I would like to interact with the other participants in the group again.	**.827**	-.163	-.141
The other participants are persons I could see having as a friend	**.820**	-.018	-.147
The other participants were warm.	**.798**	-.054	.047
The interaction with the other participants went smoothly.	**.661**	-.171	-.099
I feel held back by the group of 3 people around the table in this room.	.097	**.770**	-.110
I do not fit in well with the group of 3 people around the table in this room.	-.327	**.724**	.311
I fell uneasy with the group of 3 people around the table in this room.	-.278	**.749**	.127
How much did you want your assembly line to perform well?	.368	-.091	**-.549**
In the group of 3 people around the table in this room , members did not hve to rely on one another to complete group tasks	.046	.051	**.890**

4.3. Relation between physiology and self-report

To test the hypothesis that people who are more synchronous will perceive the cooperation as running more smoothly than people who are less synchronous, we use the three factors resulting form the PCA of the questions from the team cohesion questionnaire, that was filled out after trial five (cf. Figure 1). To see whether the average dyad score on these questions is related to the level of synchrony exhibited by the dyads we calculate the correlation coefficient of the average dyad factor scores and the CRQA synchrony measure for zygomaticus EMG and skin conductance from trial five. Trial five is chosen because it is closest to the time at which the questionnaire was filled out. Table 5 presents the full correlation matrix.

Table 5

Correlation coefficients for synchrony strength in EMG ZM (zygomaticus activity) and pEDA (skin conductance) with the five factors extracted form the team cohesion questionnaire. Synchrony measures are obtained from trial five, and *questionnaire factors* are mean factor loadings for the respective dyad members. Factor 1 captures relationship orientation and positive affect towards the group; Factor 2 captures group tension and negative affect towards the group; Factor 3 task orientation; Statistical significance is indicated by asterisks: $p < 0.05$.

Extracted Factor	Sync. EMG ZM	Sync. pEDA
Factor 1 (positive affect towards the group)	0.174*	0.143
Factor 2 (tensions within the group)	-0.094	0.181*
Factor 3 (task orientation)	-0.053	-0.155

We observe significant correlations between synchrony in zygomaticus EMG and Factor 1, as well as synchrony in skin conductance and Factor 2. The overall strength of the correlations is comparatively weak, but sensible: High degree of synchrony in zygomaticus activity (smiling) showed positive correlations with relationship orientation and positive affect towards group members. Further, high degree of synchrony in skin conductance is positively correlated with, perception of tension in the group and negative affect towards the

other group members. Note that the correlations between physiological synchrony and self-report seem mainly related to emotional aspects of cooperation (Factors 1 and 2), but absent for task oriented aspects of cooperation (Factor 3).

4.4. Relation between synchrony, team decisions, and induced emotion

Before analyzing the relation between team synchrony and team decisions, we collapsed the data from the three pre-adoption trials into a pre-adoption synchrony score, and the data from the two post-adoption trials in to a post-adoption synchrony score. To test for effects of team choice regarding the adoption of a new work routine, we construct a categorical variable "full adoption" (i.e., whether a team adopted an innovative routine during the construction process or not) with two levels, reflecting whether the teams chose to adopt the new routine consistently in *both* trial four and trial five, or not. We also test for effects of induced emotion (positive or negative) and gender (male or female team) on the physiological measures. As dependent variables, we use synchrony in phasic skin conductance (pEDA) and synchrony of the electromyogram of zygomaticus activity (EMG ZM). The factors are tested for each variable separately in a four-way repeated measures ANOVA with the between participant factors full adoption (two levels: consistent adoption of a new routine vs. inconsistent adoption/non-adoption), induced emotion (two levels: positive affect vs. negative affect), and the within participant factor trial (two levels: pre- vs. post-adoption). This is done for synchrony between team members in EMG ZM and pEDA.

Table 6

Results for the test of synchrony of zygomaticus EMG on adoption. The dependent variable is the synchrony component for zygomaticus EMG.

Factors	**Zygomaticus EMG synchrony**					
	SoSq III	**DF**	**MeanSq**	***F***	***p***	**par. η^2**

Intercept	0.03	1	0.03	0.07	= 0.797	0.001
Induced emotion	10.00	1	10.00	21.74	< 0.001	0.145
Adoption	227.57	1	227.57	12.68	< 0.001	0.100
Induced emotion:Adoption	0.26	1	0.26	0.57	=0.451	0.004
Residuals	58.90	128	0.46			
Trial	4.93	1	4.93	26.64	< 0.001	0.172
Trial:Induced emotion	0.11	1	0.11	0.58	=0.446	0.005
Trial:Adoption	0.06	1	0.06	0.30	=0.588	0.002
Trial:Induced emotion:Adoption	0.96	1	0.96	5.17	=0.025	0.039
Residuals	23.70	128	0.19			

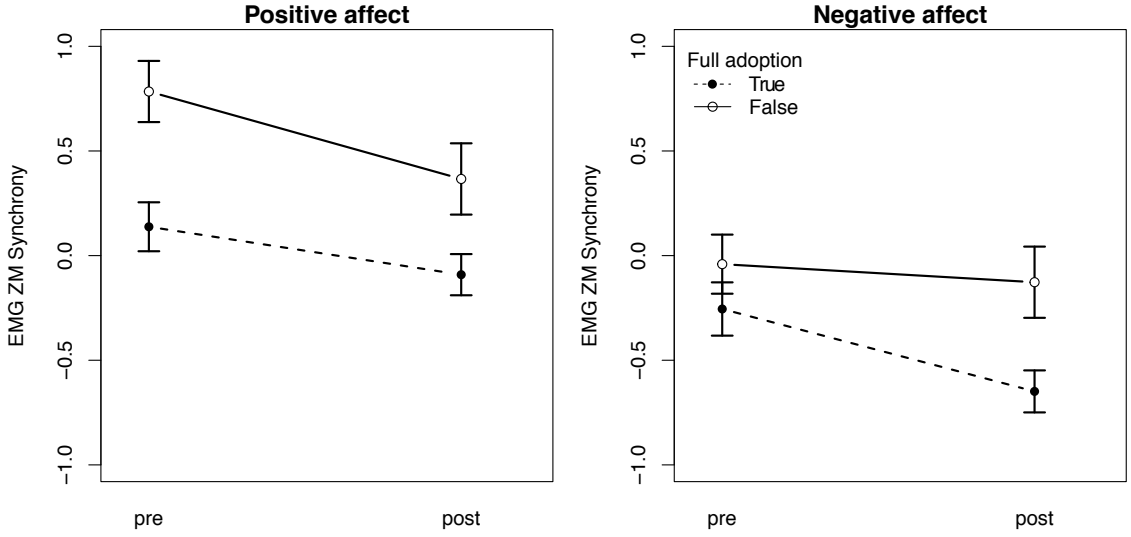

Figure 4. Synchrony score for zygomaticus major EMG. Results are plotted for teams induced in the positive condition (left) and the negative condition (right). In each plot the results for pre- and post adoption are shown for teams that adopted in both trial four and trial five (full adoption = true) as well as teams who did not adopt at all or only partially (full adoption = false). The error bars indicate the standard error of the mean. Note that synchrony scores are the factor values derived form the PCA of the three RQA measures ADL, LDL, and DET. Hence, these values can be negative. However, this does not necessarily imply asynchronous behavior, but rather corresponds to lower degrees of synchrony.

Table 7

Logistic regression of adoption of a new routine onto synchrony in zygomaticus EMG

Observed		Predicted		
		Full adoption		Correctly classified cases
		yes	no	
Full adoption	**yes**	71	10	87.7%
	no	38	13	25.5%
Overall percentage correct				63.6%

The results (including measures of effect size) are shown in Table 6. Looking at the synchrony measure for zygomaticus EMG (Table 6 and Figure 4), a main effect of induced emotion is obtained, indicating that higher synchrony in zygomaticus activity between team members when negative emotions were induced compared to when positive emotions were induced, $F(1, 128) = 21.74$, $p < .001$, $\boldsymbol{\eta^2} = .145$. A main effect of adoption is also obtained, indicating generally lower synchrony in zygomaticus activity between team members when a new routine was adopted compared to when this was not the case, $F(1, 128) = 12.68$, $p < .001$, $\boldsymbol{\eta^2} = .100$. Finally, a main effect of trial is observed, indicating generally lower synchrony in zygomaticus activity between team members after they were presented with the opportunity to adopt a new routine—irrespectively of whether they adopted the routine or not, $F(1, 128) = 26.64$, $p < .001$, $\boldsymbol{\eta^2} = .172$. None of the two-way interactions are significant, but a three-way interaction between trial, induced emotion, and adoption is obtained, $F(1, 128) = 5.17$, $p = .025$, $\boldsymbol{\eta^2} = .039$. To investigate the three-way interaction, we broke down the analysis by the factors induced emotion and adoption and conducted separate paired sample *t*-tests for trial (pre/post) for each of the four combinations of the factors adoption and induced emotion. The results of the post-hoc tests revealed that synchrony in zygomaticus EMG activity significantly decreased from pre- to post-adoption trials when teams chose to adopt a new routine, irrespectively of the induced emotion (both $t < 2.36$, both $p < .023$). However, synchrony in zygomaticus activity also decreased from pre- to post trial for teams that did not adopt a new routine when positive emotions were induced ($t(32) = 2.84$, $p = .009$), but this

was not the case for teams that did not adopt a new routine when negative emotions were induced ($t(26) = 0.72$, $p = .481$), see Figure 4.

Since a good portion of the variance of the observed main effect of adoption on synchrony in zygomaticus EMG is not moderated by the three-way interaction between trial, induced emotion, and adoption, this may suggest that synchrony is not merely an outcome of the decision to adopt a routine, but may predict whether teams adopt a new routine, even before team members are presented with the option to do so Admittedly, this is a speculative post-hoc interpretation, but it can be tested using logistic regression anlaysis: In order to test this hypothesis, we conduct a post-hoc logistic regression analysis with full adoption (yes/no) as dependent variable and synchrony in zygomaticus activity prior to the choice of adopting a new routine as predictor variable. Table 7 summarizes the results of the logistic regression: As can be seen, the degree of pre-adoption synchrony in zygomaticus EMG between team members predicts whether a team will adopt a new work routine in the future or not, $\chi^2(1) = 6.86$, $p = .009$, Nagelkerke's $R^2 = .069$.

The results for skin conductance are summarized in Table 8 and Figure 5: For skin conductance, a main effect of adoption is obtained, indicating that synchrony in skin conductance of team members is lower for teams that adopt a new routine compared to teams that do not, $F(1, 114) = 20.04$, $p < .001$, $\boldsymbol{\eta^2} = .150$. However, this main effect of adoption was moderated by an interaction effect between adoption and trial, $F(1, 114) = 40.46$, $p < .001$, $\boldsymbol{\eta^2} = .262$. To investigate the interaction effect, we broke down the analysis by the factor adoption and conducted separate paired sample *t*-tests for trial (pre/post) when teams either adopted a new routine or not. The results show that synchrony in skin conductance increased for teams that did not adopt a new routine from pre- to post adoption ($t(66) = 6.22$, $p < .001$), while the opposite was true for teams that adopted a new routine, where synchrony in skin conductance decreased from pre-to post adoption ($t(50) = -3.43$, $p < .001$), see Figure 5.

Table 8

Results for the test of synchrony of skin conductance on adoption. The dependent variable is the synchrony component for phasic EDA.

Factors	Skin conductance synchrony					
	SoSq III	DF	MeanSq	*F*	*p*	par. η^2
Intercept	0.14	1	0.14	0.25	= 0.616	0.002
Induced emotion	0.02	1	0.02	0.04	= 0.844	0.000
Adoption	10.80	1	10.80	20.04	< 0.001	0.150
Induced emotion:Adoption	0.05	1	0.05	0.09	=0.763	0.001
Residuals	61.43	114	0.54			
Trial	0.03	1	0.03	0.12	= 0.730	0.001
Trial:Induced emotion	0.96	1	0.96	4.10	= 0.045	0.035
Trial:Adoption	9.50	1	9.50	40.46	< 0.001	0.262
Trial:Induced emotion:Adoption	0.00	1	0.00	0.02	= 0.891	0.000
Residuals	26.76	114	0.24			

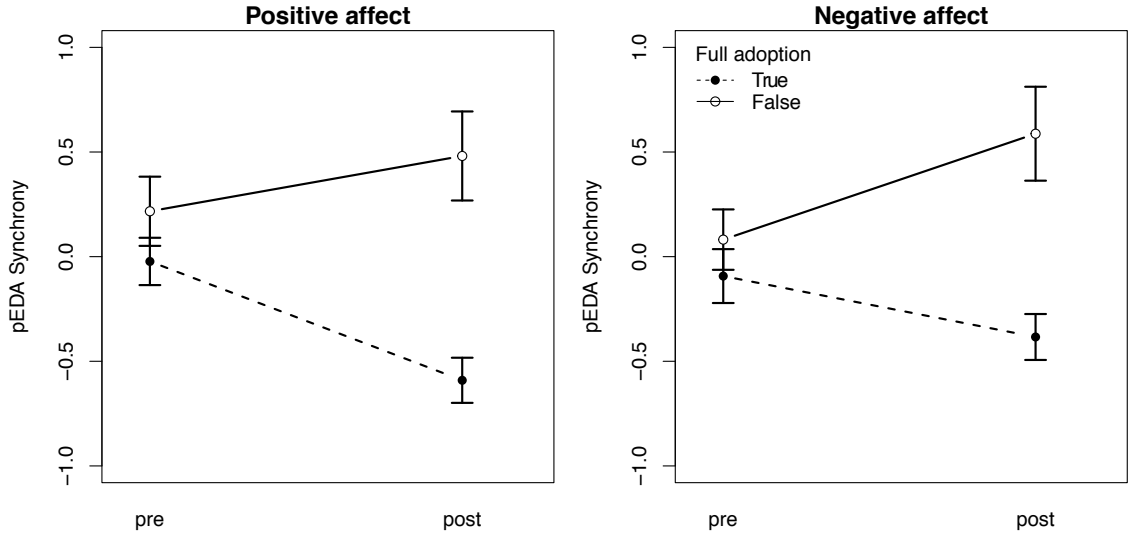

Figure 5. Synchrony score for pEDA. Results are plotted for teams induced in the positive condition (left) and the negative condition (right). In each plot the results for pre- and post adoption are shown for teams that adopted in both trial four and trial five (full adoption = true) as well as teams who did not adopt at all or only partially (full adoption = false). The

error bars indicate the standard error of the mean. Just as in Figure 4 the synchrony scores displayed here are the factor values derived form the PCA of the three RQA measures ADL, LDL, and DET. Hence, these values can be negative (corresponding to lower degrees of synchrony).

Finally, we also obtain an interaction effect between induced emotion and trial, $F(1, 114) = 4.10$, $p = .045$, $\eta^2 = .035$. Again, we break down the analysis by the factor induced emotion and conduct separate paired sample *t*-tests for trial (pre/post) when either positive or negative emotions had been induced at the beginning of the task. The post-hoc tests reveal that synchrony in skin conductance decreased from pre- to post-trials when positive emotions had been induced ($t(53) = 2.05$, $p = .046$), but not when negative emotions had been induced ($t(63) = -0.73$, $p = .465$). However, this effect is relatively minor compared to the effect of adoption on synchrony (see Table 8). A post-hoc logistic regression analysis does not reveal any substantial predictive power of the level of pre-trial synchrony in skin conductance for the adoption of a new work routine by the team, $\chi^2(1) = 2.15$, $p = .143$, Nagelkerke's $R^2 = .024$.

5. Discussion

In this study, we investigated a) whether physiological markers of team emotions exhibited synchrony, b) whether synchrony was associated with greater team cohesion, and c) how physiological synchrony was affected by induced emotion, and the adoption (or non-adoption) of new working routines.

A false-pair surrogate analysis of the physiological measures, comparing the amount of synchrony between members that were part of a team and interacted with each other to the amount of synchrony between participants that worked in different teams, showed that the physiological markers of members of the real teams exhibited a greater amount of synchrony.

This result corroborates several recent findings that show physiological synchrony in interacting dyads and groups (for recent reviews, see [53, 54]).

However, we only found synchrony for electromyographic measures of the zygomaticus major muscle ('smiling muscle') and for skin conductance, but not for heart rate or the corrugator supercilii muscle ('frowning muscle'). Obviously, heart rate synchrony was a less sensitive measure of synchrony of arousal compared to skin conductance in the present study, as only the latter revealed effects relative to the false pair pseudodyads. The failure of heart rate synchrony to reveal such effects, this may be because our task was not strongly arousing as compared to other research that showed heart rate synchronization [9]. Moreover, our task also did not systematically involve heart rate in a functional way for task performance, such as through the coupling of heart rate and breathing, which has shown to create synchronous heart rate activity in members of a choir during singing [55]. In contrast, participants were not allowed to speak during the origami production task. As for the corrugator supercilii muscle, absence of synchrony effects remain rather unclear. One possible interpretation may be that while smiling has shown to be contagious, this does not seem to be equally true for frowning [56].

Synchrony showed small, but significant correlations with self-reported measures of team cohesion. Interestingly, we found a difference in synchrony of skin conductance and synchrony of smiling. Synchrony of skin conductance was related to negative affect towards the other team members and feelings of not belonging to the team. Synchrony of smiling was positively related to team cohesion and positive affect towards team members. This shows that synchrony of smiling and skin conductance capture different aspects of team emotions with smiling synchrony relating to positive aspects and skin conductance synchrony relating mainly to negative aspects. These effects are also in line with studies that have related the level of activity in skin conductance to arousal [13] and stress resulting from social stimuli

and salience of in-group/out-group relations [57], as well as level of activity in the zygomaticus major to the valence of emotions [58].

Synchrony of zygomaticus activity and skin conductance also turned out to be sensitive measures of team emotions in relation to the decision to adopt a new routine: Generally, adoption of a new routine was associated with lower levels of synchrony in zygomaticus activity and skin conductance. However, while a decrease in skin conductance synchrony was found to be a consequence of the choice to adopt a new routine, synchrony of zygomaticus activity also predicted whether a new routine would be adopted. A possible explanation of this may be that in contrast to electrodermal activity, activity of the zygomaticus major is related to positive emotional expression, and also has a signaling function. Lower degrees of synchrony in zygomaticus activity might be an indicator of greater emotional heterogeneity of the groups, which has been associated with greater creativity in team problem solving [59].

To summarize, adoption of a new routine was always associated with a decrease in synchrony, indicating that higher levels of synchrony might either act as a stabilizer of established behavior, leading to a decreased tendency to take risky or novel choices. Also, low levels of synchrony emerged as a clear marker of new activity patterns (in this case adoption of a new work routine).

Our results show that synchrony measures of emotion-related physiological activity are sensitive measures of group processes, such as the reaction to emotional induction or collective choice. Also, synchrony measures yield potentially complementary information, theoretically and empirically, relative to measures of the level of physiological activity: While measures of level of activity quantify the relative absence or presence of the expression of an emotional behavior, synchrony measures provide information about how the expression of emotional behavior is coordinated in teams. However, despite being promising,

synchrony measures are relatively new and future work is needed to more firmly establish their role as indicators of emotional expression and interaction.

5.1. Future research

By applying synchrony measures to physiological measures related to emotion, we have shown that synchrony develops spontaneously in newly formed teams, and is correlated with self-reported measures of team cohesion. Moreover, synchrony is an indicator of new patterns of activity and a potential predictor of teams' decision to adopt novel and innovative solutions. These new results hold promise that team emotions as interpersonal synchrony can shed light on the emotional processes occurring in teams as they perform their tasks. However, in order to establish such a dynamical view on team emotions as a complement to more established approaches further studies using synchrony measures are needed.

In our analysis we found a decrease in synchrony of skin conductance in teams that adopted the new routine, whereas teams that did not fully adopt experienced an increase in synchrony of skin conductance throughout the experiment. This raises a final question for future research, viz. how this disruption of synchrony evolves over time. One way to investigate this question is by performing a more fine grained analysis of the time development of the synchrony measures by applying a time-dependent analysis of synchrony [40].

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