Strengthening the link between science and arts: How dance-like movements alter the neural correlates of human connectedness?

Bachelor's Project Thesis

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Abstract: When involved in social processes, people frequently interact with each other in subtler ways they are aware of. Their heart rate, breathing rhythm and brain activity can synchronize during joint actions. These are thought to constitute the physiological markers of human connectedness. This study aimed to investigate how inter-brain synchrony within dyads is affected by joint movement in the social as compared to nonsocial conditions. The participants danced in the absence or presence of touch, gazing or synchronous movement with their data being recorded via EEG hyperscanning. The results suggest a trend towards there being more synchrony between brains when participants are facing compared to when they are not facing each other in the theta frequency (7-9 Hz) in the right frontopolar ($Fp2$) and centroparietal ($FC2$) regions. The same is observed in the beta frequency (14-24 Hz) in the frontopolar cortex ($Fp1$). Additionally, more inter-brain synchrony was observed during synchronous compared to asynchronous movement in the theta and alpha (9-14 Hz) frequencies. Moving together as if the participants had one body pointed to an increase in inter-brain synchrony in the prefrontal ($Fp2$) and occipital ($PO4$) areas in theta frequency; and in the frontal ($F7$) cortex in the beta frequency. However, most of the results did not survive the multiple comparison problem correction. Comparing the data of professional dancers with subjective ratings of connectedness did not show a correlation. Subsequent research with bigger sample sizes is necessary to confirm touch, gaze and synchronous movement make the humans feel more connected.

1 Introduction

Humans are social beings and social cognition — being able to comprehend each other's intentions, feeling and thoughts — points to our unique characteristics, to make use of social cognition to build civilizations and culture (Adolphs, 2009). In this vein, human connectedness is the crux, although there is yet no explicit definition of what it is. A possible description is "when a person is actively involved with another person, object, group, or environment, and that involvement promotes a sense of comfort, well-being and anxiety reduction" (Hagerty, Lynch-Sauer, Patusky, and Bouwsema, 1993, p.293).

1.1 Mother-Child Synchronization

It is worth noting that humans seem to be born with this capacity of becoming connected, as from the early days there is a special bond between the mother and her child. Thirty years ago, Field, Healy, and LeBlanc (1989) performed a study of cross-spectral analysis of shared synchrony of behavioral states and heart rate between depressed and nondepressed mothers and their infants. Their findings suggested there was a greater coherence in both variables between the nondepressed as opposed to the depressed dyads. A more recent study, focused on the connection between the mother and the fetus. By employing synchrograms, Van Leeuwen et al. (2009) found evidence for short epochs of heart rate synchronization between the two in uncontrolled conditions as the mother engaged in spontaneous breathing. A more recent study of Miller et al. (2019), investigated the inter-brain synchrony of mother-child dyads using functional near-infrared spectroscopy (fNIRS) hyperscanning. Their results putatively indicated there was an increase in the inferior prefrontal cortex during mother-son engagement in cooperative tasks as opposed to independent tasks. In addition there was an increase in the frontopolar cortex in mother-son and mother-daughter dyads during the cooperative versus the independent tasks.

1.2 Respiratory and Heart Rate Variability Synchronization

Searching for the physiological markers of social connectedness and their triggers in the world of adults, there is evidence of spontaneous synchronization of arm movements and respiratory rate, although in different conditions (metronome- and music-associated conditions) (Codrons, Bernardi, Vandoni, and Bernardi, 2014). Moreover, Müller and Lindenberger (2011) detected an increase in phase synchronization for respiratory and heart rate variability (HRV) during singing of a choir compared to a rest condition, as well as a higher respiratory and HRV during unison singing as compared to multiple voice parts. These findings support the idea of the individuals striving to be a social unit (Marsh, Richardson, and Schmidt, 2009), thus making room for socioemotional connectedness to emerge when humans engage in joint actions.

1.3 Inter-Brain Synchronization

A considerable number of studies have focused on inter-brain synchronization in various social circumstances. One among many is the study of Jiang et al. (2012), in which participants engage in face-to-face or back-to-back monologue and dialogue respectively. Their study analyzed inter-brain synchronization using fNIRS hyperscanning and revealed a significant increase in the left inferior frontal cortex during face-to-face dialogue condition as compared to the back-to-back conditions. However, the activity of this area did not differ from the face-to-face monologue condition, suggesting the recorded results are a marker of the face-to-face communication. Another study supporting the impact of face-to-face interaction on inter-brain synchrony is that of Honghong et al. (2015), in which participants had to engage in a two-person economic exchange. The results, recorded via fNIRS hyperscanning, indicate an increase in the right tempo-parietal junction during face-to-face trials as compared to the face-blocked ones (the participants being separated by a board). The increase in the aforementioned area was associated with shared intentionality between the dyads. These are in line with the construct that face-to-face interactions facilitate the sharing of psychological states between people (Gilbert, 1992; Searle, Willis, et al., 1995).

An interesting study on inter-brain synchrony performed via EEG hyperscanning is that of Goldstein, Weissman-Fogel, Dumas, and Shamay-Tsoory (2018), as it proves that touch has analgesic effects in heterosexual romantic partners and increases inter-brain synchrony in the alpha-mu (8-12 Hz) frequency band. The findings indicate that holding hands during pain administration leads to increased brain-to-brain coupling in the right hemisphere of the watcher and in the central brain regions of the pain target.

1.4 The aim of the present study

Since the prior studies provide examples of human connectedness arising in various ways of communication, it could be interesting to analyze the effect of dancing as well. The literature defines dance as "part of the human constitution and a basic force in social life, and not merely the consequence of human intention in some particular time and place" (Hagerty et al., 1993, p.89). On these grounds it would be intriguing to have a closer look at the neural correlates of dancing people during their performance and examine inter-brain synchrony from a different view.

Connectedness can be achieved as a repercussion of different interaction ways, e.g. via touch (Goldstein et al., 2018) and other non-verbal social interaction such as gestures (Dumas, Nadel, Soussignan, Martinerie, and Garnero, 2010), synchronous movement (Codrons et al., 2014) or facing each other (Jiang et al., 2012; Honghong et al., 2015). The study could investigate the effects of the various methods of achieving the state of human connectedness as mentioned above by combining them with dance. Along these lines a research question was formulated *How does moving in various social versus nonsocial conditions affect inter-brain synchrony?*

In order to obtain a relevant answer for the research question, dyads of ordinary people were hyperscanned using EEG while dancing in various experimental conditions that implemented these means. The independent variable *connectedness* was further subdivided into two primary categories: social and nonsocial. In the social conditions the examined effects on inter-brain synchrony were those of moving while facing versus not facing, moving synchronously versus asynchronously, moving simultaneously as one single body or performing dance-like movements in a dialogue manner. During the nonsocial conditions, the subjects were invited to dance alone or shift their focus away to a prop, after successfully engaging in one of the social conditions.

Based on the previous studies, it was hypothesized that inter-brain synchrony would be higher for the conditions in which the participants could tune into each other. Namely the following sub-hypotheses were empirically examined: (*i*) there would be higher inter-brain synchrony during the facing conditions as opposed to not facing (*ii*) there would be higher inter-brain synchrony during synchronous movement as opposed to asynchronous (*iii*) there would be higher inter-brain synchrony in the social conditions involving touch and moving in a dialogue-like manner than in the nonsocial conditions (moving alone or shifting the focus away to a prop).

To test the hypothesis empirically it was looked at three frequency bands: *theta* (7-9 Hz), *alpha* (9-14 HZ) and *beta* (14-24 Hz). The rationale for choosing the theta band was its association with cognitive and affective functions (Kahana, 2006; Krause, Viemerö, Rosenqvist, Sillanmäki, and Åström, 2000). The beta band was chosen for its association with motor and rhythmic processes (Pineda, 2005; Pavlidou, Schnitzler, and Lange, 2014). Although the mentioned studies report the findings within subjects, the brain activity in these frequency bands was found relevant to the task of this research, hence the assumption was that there would be higher inter-brain synchrony between subjects as well. The alpha band was chosen as, aside from being relevant to motor processing, it is believed to represent the most robust band for brain-to-brain coupling (Dumas et al., 2010).

Although the expectations were that higher inter-brain synchrony would be detected in the frontal and central regions for the theta band; in the parietal and occipital regions for the alpha band and in the parietal area for the beta band, all the cortical brain areas were analyzed. The reasoning was that the waves of each frequency band still manifest themselves all over the brain and this approach was considered best for new findings.

1.5 Connecting physiological data with the subjective experience

To be able to have a better understanding of the human connectedness, it is important to take into consideration the subjective experience. For this matter, a similar experiment was conducted in which professional dancers were invited to dance while engaging in various conditions during the performance. Their physiological data was collected using EEG hyperscanning, in the same way as it was done with the non-professional dancers. The subjective experience of connectedness was acquired by asking four students to asses whether they thought the dancers were connected or not via the BORIS software (Friard and Gamba, 2016). They had to rate the connectedness guided by different behavioural variables among which mirroring, touch and interaction. Afterwards, the results of the inter-brain phase synchrony in each frequency band were correlated with the subjective experiences. The expectations were that higher inter-brain synchrony would be associated with higher ratings of connectedness.

2 Methods

In order to be able to answer the research question *How does moving in various social versus nonsocial conditions affect inter-brain synchrony?*, the following procedure was conducted to obtain a statistical measure of inter-brain synchrony that could be compared between various ways of moving simultaneously.

2.1 Participants

Altogether 50 people voluntarily participated in the experiment, with the age ranging from 18 to 35 years old. The recruitment took place by word of mouth and advertisements on a Facebook group. The background of the participants was diverse, however none of those involved in this experiment were professional dancers. Subsequently, all the subjects were grouped in dyads. This resulted in a number of 25 dyads, with different gender pairings. The relationship between them varied from strangers to friends or spouse. The study protocol was conducted in accordance with the Declaration of Helsinki, and each participant was invited to sign an informed consent before engaging in the experiment. As a remuneration for participating in the study, everybody received 16 euros, for attending experimental sessions of two hours with pauses for conversation and breaks.

2.2 Equipment and procedure

Each participant was invited to perform the task which involved hands and body movements at the rhythm of 80 bpm metronome beat, allowing them to move synchronously in all the conditions. The use of a metronome was of crucial importance in the conditions in which the participants had to dance synchronously while not facing each other. Since there was no predetermined choreography, the participants could perform whatever movements they chose. However, they had to adhere to the relevant instructions on what type of movement they had to perform.

To be able to properly inspect the correlation between joint movement and other factors that may contribute to the achievement of inter-brain synchrony, such as touch, gazing and synchronous movement, the participants were asked to perform under different conditions. These can be further divided into two categories: social and nonsocial conditions.

In the social conditions the subjects had to move while combining different cases when the literature suggest there is increased synchrony. They danced while *facing synchronously* and *asynchronously*, the same procedure was followed for the not facing condition, *not facing synchronously* and *not facing asynchronously*. The next two conditions were inspired by a series of dance performances that took place in the Spring of 2019, in which dancers explored alternative ways of connecting with each other through movement. In the first case they were dancing in a *dialogue*-like manner, moving alternatively while responding to the partner's movements. The other condition was designed to control for the touch effect, and the participants were invited to move together as having *one body*.

During the nonsocial conditions the participants had to dance *alone* or to dance with a prop. In the scope of this report, the latter condition is referred to as shifting the focus away or *shift of focus*. This condition was entered when the dyad was firstly engaged in the *dialogue* condition, once the performance in the *dialogue* condition went smoothly they could enter the *shift of focus*.

2.3 EEG recording

Hyperscanning refers to the simultaneous recording of the neuroelectric activity of different participants with electroencephalography (EEG). In this experiment each dyad was hyperscanned using BioSemi's Daisy-chain technology. Each dance segment lasted for two minutes and was recorded with the BioSemi 32-channel system and six facial electrodes: two on the mastoids, one below and above the eye and one to the left and the right of the eyes, as shown in Figure 2.1. The purpose of the mastoid electrodes was for referencing, whilst those around the eyes were placed for catching the eye-movement artifacts. The electrode placement was in accordance with the international 10/20 system, as portrayed in Figure 2.2, accompanied by a video recording. Initially, the Cz electrode was used as the reference signal, however after preprocessing it was the average reference. The sampling rate was 512 Hz and the impedance was below 40 kΩ.

In the case of the current study, the participants were slightly limited by remaining fairly stationary and confined their movements mostly to arm movements to prevent movement artifacts in the EEG recording. The recordings for each of the different conditions lasted for two minutes. After the sessions, the participants were invited to evaluate how connected they felt during the task. The experiment and data collection were conducted in the city of Groningen, The Netherlands.

Figure 2.1: Placement of the electrodes on the dancers

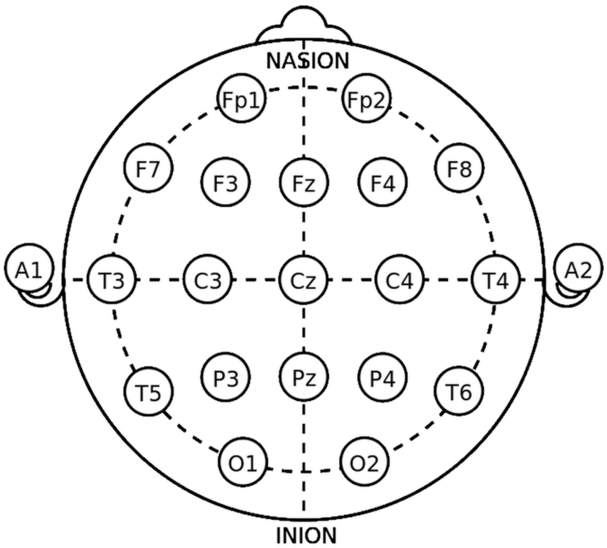

Figure 2.2: International 10/20 electrode placement system

2.4 Data processing and analysis

EEG preprocessing

The preprocessing step was carried out in Matlab by employing the Fieldtrip toolbox (Oostenveld, Fries, Maris, and Schoffelen, 2011). First of all, a low-pass

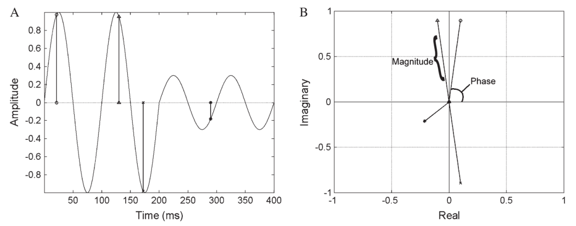

Figure 2.3: A) Time domain representation of a signal, where each vertical line indicates a different time point of the wave B) Frequency domain representation of the four time points in A, where the lines from the origin to the complex points illustrate the magnitude and the phase angle is formed with the x-axis

band filter was applied at 40 Hz to remove higher frequency muscle activity from the EEG recording. The data were down-sampled to 256 Hz and split into segments of one second. This resulted in about 120 trials for each two minute segment. All the patterns of artifactual activity (which can be caused by a combination of channels) were identified via visual inspection. Compared to the other patterns, these produced extremely steep spikes, corrupted by noisy signals (eye movements, muscle activity, heart beat and eye-blinks). The signals classified as artifactual activity were removed by the means of independent component analysis (ICA).

Time-frequency analysis

Once the data were prepared, the analysis was performed separately for each frequency band of *theta* (7-9 Hz), *alpha* (9-14 Hz) and *beta* (14-24Hz). The EEG signal was transformed into the time-frequency domain via a spectral decomposition, which resulted in a complex number for each time point. These contained information about both time and frequency domains, as shown in Figure 2.3 (Roach and Mathalon, 2008). Figure 2.3 B) represents the amplitude of the signal in A) via the magnitude of the line from the origin to the complex data point, while the phase angle is the same as the angle formed by the magnitude vector and the x-axis.

Subsequently, the phase angle was extracted from each segment of the EEG data, which had been subdivided into 1-second samples; this allowed to accurately determine whether two electrodes were synchronized. All the phase synchrony was averaged over these time-windows. The phase angle consistency was calculated per dyad, per electrode, per experiment condition and frequency band. The purpose was to determine whether two electrodes were synchronized. To achieve this it was necessary to compare the analogous channels (e.g. Cz and Cz) for the two individuals. After preprocessing, the data of the respective dyad were convolved with a Hanning taper to compute the time frequency-representations of the signals. The rationale behind using a multitaper method was that it is very frequency-specific (van Vugt, Sederberg, and Kahana, 2007). Its implementation takes the data and the taper and computes their Fourier transform and performs the element-wise multiplication in the frequency domain (Oostenveld, 2020). Consequently, the consistency was computed with the phase-locking value, which has a sensible time-resolution (<100ms) (Lachaux, Rodriguez, Martinerie, and Varela, 1999) and is more suitable for quantifying neural synchronization than other methods like spectral coherence (Lowet, Roberts, Bonizzi, Karel, and De Weerd, 2016). Next, the magnitude of the synchrony between the corresponding channels within-trials was evaluated, (van Vugt et al., 2020). A magnitude of one suggests perfect synchrony, while that of zero — complete absence (Lachaux et al., 1999).

Statistical analysis

Once the previous step was accomplished for all the dyads, in all three frequency bands (theta, alpha and beta), a linear mixed effects (LME) model was run. It possesses many advantages over other approaches, such as ANOVA, as it takes into account the effects unfolding during the course of the experiment (like fatigue). It is more robust to violations of sample sizes and independence between variables; it secures a better statistical power and a lower Type-I error rate than ANOVA. Moreover, the LME does not require averaging over trials, hence allowing to bring the longitudinal effects in the model (Baayen, Davidson, and Bates, 2008). The linear mixed effects model was implemented in R's *lmerTest* package.

Since the comparisons were performed for 32 electrodes, within and between subjects, this arose the Multiple Comparisons Problem (O'Neill and Wetherill, 1971). Therefore, after running the linear mixed effects model, all the p-values were adjusted using the *p.adjust()* function from R's *stats* package. The applied adjustment method was Holm, as it is more powerful than the Bonferroni method (Aickin and Gensler, 1996) and less conservative (Chen, Feng, and Yi, 2017).

2.5 Correlating the physiological data with the subjective experience

Particpants

For this second part of the study the participants were two professionals (see Figure 2.1) specialized in contemporary dance from the Random Collision

Dance Company, participating voluntarily in the experiment. The raters were four volunteering students from the University College Groningen; all with different backgrounds, yet united by their common interest in how people connect to each other.

Equipment and procedure

The same approach and equipment was used to record the data in this second experiment: EEG hyperscanning and video-recordings. However, the dancers were not limiting themselves and were moving naturally. During the performance they transitioned through various conditions such as dialogue — in which the dancers created a dialogue between their actions, without direct interaction; kinetic mirroring — moving in choreographed synchrony; shift of focus — directing the focus from each other to the audience; and moving as one — the dancers moved as one in non-choreographed unison.

The subjective ratings were collected using the BORIS software (Friard and Gamba, 2016). The behavioural variables were touch — indicating the time-point when the dancers touched; interaction — denoting when they danced together, responding with their movements to each other; and mirroring — when the dancers synchronously preformed the same movements.

The dance performance took place in a tour through seven cities of The Netherlands as part of the Moving Futures festival in 2019. The data analyzed in this study were recorded in Utrecht, Tilburg and Amsterdam, the recordings from the other cities were discarded due to technical reasons.

Data processing and analysis

The EEG data preprocessing and the time-frequency analysis were the same as in the previous experiment. However, the inter-brain phase synchrony was computed only for the channel-pairs which were identified as statistically significant in the experiment with the non-professional dancers.

The subjective ratings of each student were extracted for the available EEG segments and summed up per behavioural variable. This way when all four raters agreed there was connectedness between the dancers, the rating value for the specific time-point was the highest. Next, the two vectors — with the inter-brain phase synchrony values per identified channel-pair at each time-point and the one with the subjective ratings — were correlated using the *corrcoef()* function in Matlab.

3 Results

In the search of the neural correlates of human connectedness, different contrasts of social movement were analyzed. The predictions for this study were that moving synchronously would increase inter-brain phase synchrony as compared to moving asynchronously; moving while facing would lead to a greater synchronization as opposed to not facing. When comparing social and nonsocial conditions, the aim was to control for the effect of touch, gaze and synchronous movement. The predictions were that moving simultaneously in a dialogue-like manner or as one single body, would increase the inter-brain phase synchronization as compared to the nonsocial conditions: moving the shift of focus away or alone.

3.1 Inter-Brain Synchrony in the Theta Frequency Band (7-9 Hz)

After running the linear mixed effects model for the theta frequency band (7-9 Hz), the results revealed the differences in inter-brain synchrony between the conditions, at a p-value significance threshold of $p < .02$.

There was a significant increase in the phase-locking value in the frontocentral ($Fc2$) cortex during synchronous movement as compared to asynchronous joint movement (see Table 3.1).

When comparing the facing and the not facing conditions, evidence supports an increase in the frontocentral channel ($Fc2$), this difference is significant enough to survive the multiple comparisons problem adjustment at $p < .05$ ($p_{Fc2} = .039$, corrected). Other channels that were significant at a threshold of .02 before adjustment are located in the parieto-occipital ($PO3$) and in the right frontopolar ($Fp2$) cortices. A possible interpretation could be due to a higher emotional processing of the emotions of the other person in the facing condition (Jiang et al., 2012). The increase in the frontocentral channel ($Fc2$) in the synchronous versus asynchronous conditions might be associated with more attention dedicated to motor processing, especially considering the circumstance of moving synchronously while not facing is a more difficult task (Farnsworth, 2019).

Inquiring how the dance-inspired conditions would differ from the nonsocial ones, the inter-brain synchrony between the subjects while they moved as a single body or in a dialogue-like manner was compared to moving alone and shifting the focus of attention away.

The results indicate that at a threshold of $p < .02$ there is an increased inter-brain phase synchrony in the occipital (Oz), parietal ($P4$) and centroparietal ($PO4$) cortices, when comparing the moving as one single body condition with shifting the focus away. Moreover, the inter-brain synchrony increase in the centroparietal ($PO4$) area was robust enough to survive the multiple comparisons problem (Figure 3.1). Once more, this could be an indication of directing more attention to planning one's movements and predictive timing of movements (Arnal and Giraud, 2012) when performing in the social conditions.

It was found that comparing the movement as one body with moving alone suggests an increase in inter-brain synchrony in the parieto-occipital ($PO4$) and the right frontopolar ($Fp2$) cortices. Again these trends indicate there might be more visual attention and the participants might be focusing more in moving simultaneously as they have to plan the movements and mentalize their social perception.

Alternatively responding to the partner's movements in the dialogue conditions points to an increase in inter-brain synchrony in the parietal region ($P4$) as compared to shifting the focus away to an object. Once more this might indicate more movement coordination, yet the trend is weak.

The mean inter-brain phase synchrony for the significant channels in the different conditions is displayed in Table 3.2 and the visualization of the results in Figure 3.1.

3.2 Inter-Brain Synchrony in the Alpha Frequency Band (9-14 Hz)

Next, the question of whether different ways of moving together would affect the inter-brain synchrony in the alpha frequency band (9-14 Hz) arose. The results are reflected in Table 3.3. The inter-brain phase synchrony is observed to increase at a p-value threshold of .02 in the synchronous versus asynchronous conditions in the anterior frontal ($AF3$) and occipital ($O2$) areas. This might be caused by being more aware of one's movements when trying to be in synch with the partner (Plotkin and Cohen, 1976). Interestingly, there is evidence for less synchronization during the facing versus the not facing conditions, mainly in the occipital cortex ($O1$, Oz), as visualized in Figure 3.2. However, no results survive the multiple comparisons problem, so a future study with a bigger sample size is necessary to understand what happens.

Another interesting finding is the tendency of desynchronization in the frontocentral cortex ($FC5$) in the dialogue versus shifting the focus away (Figure 3.2). This could imply when the subjects engaged in dance movements with the prop they actually had more inter-brain synchrony as compared to moving together in a dialogue-like manner. Yet as the result is significant (see Table 3.3) only before multiple comparison correction over one single channel, no certain conclusions can be drawn.

3.3 Inter-Brain Synchrony in the Beta Frequency Band

Investigating the effects of moving together in the beta frequency band (14-24 Hz) revealed an increase in inter-brain synchrony in the left frontopolar cortex ($Fp1$) during the facing versus not facing conditions. A possible explanation could be the participants were more actively concentrating on the task when they were facing each other. However, since the result is only significant before multiple comparison correction this might be solely noise.

Miscellaneous results were identified when comparing the social conditions with the nonsocial ones, see Table 3.5 and Figure 3.3. Dancing in a dialogue-like manner is associated with a decrease in inter-brain synchrony in the parietal region (Pz), yet the result is only significant at a .02 threshold before multiple comparison correction. This might be due to the participants being more in synch while actually shifting their focus away rather than when moving together. When dancing with the prop, for example, they had to plan for grasping, fine finger movements and movement execution, which would in turn lead to more inter-brain synchrony in the beta frequency band in the found parietal regions (Farnsworth, 2019).

When comparing dancing as one body with shifting the focus away it can be noticed that there is a trend of increased inter-brain synchrony in the frontal region ($F7$). Conversely, the channels in the parietal regions ($P3$, Pz) show a decrease in inter-brain synchrony when moving together as opposed to shifting the focus away to a prop, where Pz survives the multiple comparison adjustment ($p_{Pz} = .049$, after correction). Future studies with bigger sample sizes are necessary to understand why these effects arise.

3.4 Correlation between the EEG data and the subjective ratings

Lastly, it was asked whether during the moments with higher inter-brain phase synchrony between dyads there would be perceived more connectedness from a subjective point of view. The most salient results from all three cities (Utrecht, Amsterdam and Tilburg) are presented together.

The highest correlations were detected during the behavioral variable of interaction. There was a significant positive correlation between the inter-brain phase synchrony in the parieto-occipital area ($PO3$) in the theta frequency band and the subjective rating ($r(806) = 0.10$, $p = .0036$). The more the dancers were interacting, their brains tended to

Table 3.1: Table with uncorrected p-values of the significant channels (p < .02) in the Theta frequency band (7-9 Hz). The chi-squared indicates how well including the effect of the conditions models the inter-brain phase synchrony for the particular channel-pair. Take me back to text

Condition	Channel	Coef β	SE (β)	P-val	χ^2
Facing vs not Facing	PO3	0.0078	0.0024	0.00169	9.8589
	Fc2	0.0082	0.0025	0.00124	10.427
	Fp2	0.006	0.0025	0.0174	5.6528
Synchronous vs Asynchronous	Fc2	0.0067	0.0025	0.0078	3.0768
One Body vs Alone	PO4	0.0078	0.0024	0.0026	18.079
	Fp2	0.0094	0.0035	0.0085	22.831
One Body vs shifting the focus away	Oz	0.0087	0.0025	0.0128	11.717
	PO4	0.0011	0.0035	0.00155	18.079
	P4	0.0095	0.0035	0.00642	12.272
Dialogue vs shifting the focus away	P4	0.001	0.0034	0.00366	12.272

Table 3.2: Theta frequency band (7-9 Hz) mean phase-locking value (PLV) per channel.

Channel	Condition	Mean PLV
PO3	Facing	0.3737
	Not Facing	0.3659
Fp2	Facing	0.3744
	Not Facing	0.3683
	One Body	0.3782
	Alone	0.3687
Fc2	Facing	0.3747
	Not Facing	0.3665
	Synchronous	0.3740
	Asynchronous	0.3672
PO4	One Body	0.3800
	Alone	0.3693
	Shifting the Focus away	0.3688
Oz	One Body	0.3733
	Shifting the Focus away	0.3645
P4	One Body	0.3743
	Dialogue	0.3749
	Shifting the Focus away	0.3647

synchronize and they were perceived subjectively as being more connected. So in this case one could say the physiological marker of connectedness is in line with the subjective experience, yet there is only a weak trend.

Surprisingly, there were some results pointing to a negative relationship between the inter-brain phase synchrony and connectedness. In the alpha frequency band, the students thought the dancers were less connected while their brains synchronized more in the left occipital $O1$ (r(726) = -.098, p = .008, see Figure 3.4) and central occipital Oz (r(806) = -.074, p = .036) areas. A possible explanation could be as the dancers were visually more focused, there seemed to be less connectedness. Figure 3.5 provides a summarized visualization of the brain areas and the direction of the correlations. Since the found results are very weak, they should be interpreted with a grain of salt.

4 Discussion

The aim of the current study was to gain insights into the neuronal correlates of human connectedness by computing the inter-brain phase synchrony of dancing people. To make this possible, ordinary people were invited to dance in various social conditions. The assumptions were there would be higher inter-brain synchrony in the conditions in which the participants tuned into each other via synchronous as opposed to asynchronous movement; while facing as opposed to not facing; while moving in a dialogue-like manner and while moving together as one body as opposed to moving alone or shifting the focus away to a prop. These expectations were on the ground of evidence of increased inter-brain synchrony as marker of connectedness between partners during gaze (Jiang et al., 2012; Honghong et al., 2015) and touch (Goldstein et al., 2018).The present study supplies evidence supporting the idea of an increased inter-brain phase synchrony in the social conditions. The most substantial effects are in the lowest frequency band of the three: theta (7-9 Hz).

4.1 Effects of dancing while facing versus not facing

Previous research suggests there is an increase in inter-brain synchrony in humans when they are engaged in face-to-face dialogue compared to face-to-face monologue or back-to-back dialogue and monologue, (Jiang et al., 2012). It was tested whether this holds for dancing as well (controlling for the effect of gaze in verbal and nonverbal communication). It was detected that being able to establish visual contact with the partner while dancing in varied social conditions leads to a significant increase in inter-brain synchrony in the theta (7-9 Hz) frequency band, in the parieto-occipital ($PO3$), right frontocentral ($FC2$) and right fron-

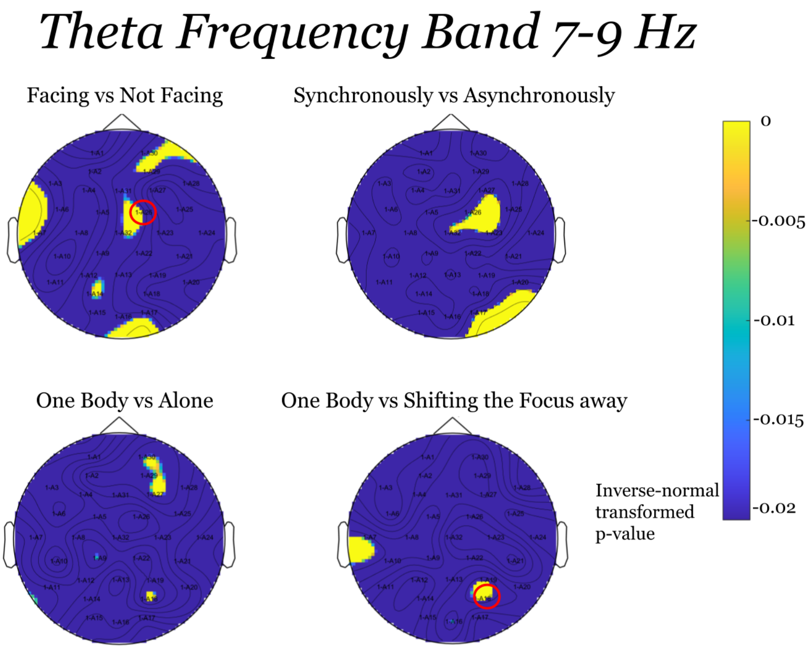

Figure 3.1: The effects of movement on the inter-brain synchrony at $p < .02$. Yellow means highly significant, while dark blue - no significance; circled in red – the channels which survived the multiple comparisons correction.

Table 3.3: Table with p-values of the significant channels (p < .02) in the Alpha frequency band (9-14 Hz). The chi-squared indicates how well including the effect of the conditions models the inter-brain phase synchrony for the particular channel-pair. Take me back to text

Condition	Channel	Coef β	SE (β)	P-val	χ^2
Facing vs not Facing	O1	-0.0056	0.002	0.00621	7.489
	Oz	-0.0055	0.0024	0.007	7.273
Synchronous vs Asynchronous	AF3	0.0057	0.002	0.00454	8.054
	O2	0.0049	0.002	0.017	1.359
Dialogue vs shifting the focus away	FC5	-0.0087	0.0028	0.0168	16.293

Table 3.4: Alpha frequency band (9-14 Hz) mean phase-locking value (PLV) per channel.

Channel	Condition	Mean PLV
O1	Facing	0.3205
	Not Facing	0.3262
Oz	Facing	0.3194
	Not Facing	0.3249
AF3	Synchronous	0.3226
	Asynchronous	0.3168
O2	Synchronous	0.3246
	Asynchronous	0.3197
FC5	Dialogue	0.3161
	Shifting the Focus away	0.3250

topolar ($Fp2$) cortices. This could be explained by the link of the theta band to the processing of emotions, in the frontal electrodes (Krause et al., 2000). In the act of facing the dance partner, his or her emotions can be read as opposed to the not facing conditions.

In the alpha frequency band (9-14 Hz), there was a significant decrease in inter-brain synchrony in the facing condition as compared to the not facing one in the occipital areas ($O1$ and Oz). This finding is antithetic with previous studies. Since the alpha frequency band is associated with motor perception, because of activation in the mirror neuron system (Pineda, 2005), one would expect an increase in the phase-locking synchrony during the facing set-up. Nonetheless, there are controversial opinions, e.g. Hobson and Bishop (2016) claim that it should not be taken for granted that the alpha band is a marker of the human mirror neuron system activation. Since the found electrodes in this study represent different areas than the previous research, this might be a direction for a subsequent research to investigate what exactly caused the desynchronization, or if it is just a consequence of recording noise. One should also keep in mind none of the results survive the multiple comparison problem correction.

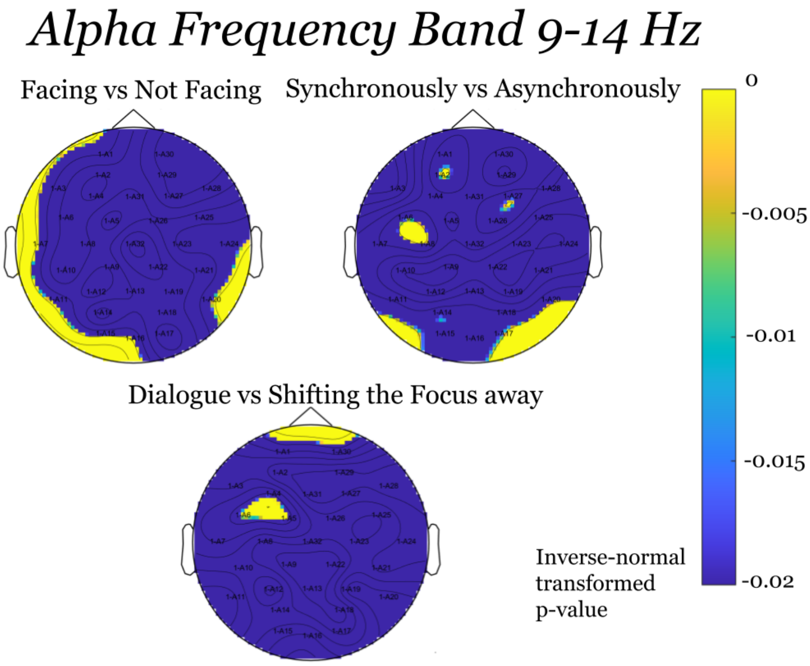

Figure 3.2: The effects of movement on the inter-brain synchrony at $p < .02$. Yellow means highly significant, while dark blue - no significance. Note that here there is a significant increase in inter-brain synchrony only in the synchronous as compared to asynchronous movement. The other two figures show the areas with a significant desynchronization.

Table 3.5: Table with p-values of the significant channels (p < .02) in the Beta frequency band (14-24 Hz). The chi-squared indicates how well including the effect of the conditions models the inter-brain phase synchrony for the particular channel-pair. Take me back to text

Condition	Channel	Coef β	SE (β)	P-val	χ^2
Facing vs not Facing	Fp1	0.0037	0.001	0.0188	5.519
One Body vs shifting the focus away	Pz	-0.008	0.0022	0.000182	19.17
	P3	-0.006	0.0022	0.0058	10.674
	F7	0.005	0.0022	0.0162	10.652
Dialogue vs shifting the focus away	Pz	-0.0053	0.0022	0.0168	19.17

An increase in the inter-brain synchrony was recorded in the beta (14-24 Hz) frequency band. This is in line with previous research of Pavlidou et al. (2014), who emphasized the beta band is not exclusively associated with the motor processes *per se*, but also with their visual processing. Hence, there is a chance of more incoming signals in the left frontopolar ($Fp1$) region. Yet the increase detected in the respective region is relatively weak as it does not survive the multiple comparisons problem correction.

Summing up, the results suggests there is more inter-brain synchrony in the theta frequency band over the frontal cortices, associated with emotional processing. Since processing each other's emotions is associated with being connected, it can be concluded that touch may represent a way of increasing human connectedness. This finding is in line with the study's hypothesis.

4.2 Effects of dancing synchronously versus asynchronously

To explore the effects of synchronous movement on inter-brain phase synchrony, the contrasts between the synchronous conditions (facing synchronously and not facing synchronously) and the asynchronous conditions (facing asynchronously and not facing asynchronously) have been analyzed. The results indicate there was a significant increase in the phase-locking value in the theta frequency band (in the frontocentral area $Fc2$) and alpha frequency band (in the left frontal $AF3$ and the right occipital $O2$ areas). This outcome corroborates the idea of Tunçgenç and Cohen (2016), namely that only moving together does not result in bonding between individuals, yet moving synchronously leads to a positive change. The increase of inter-brain

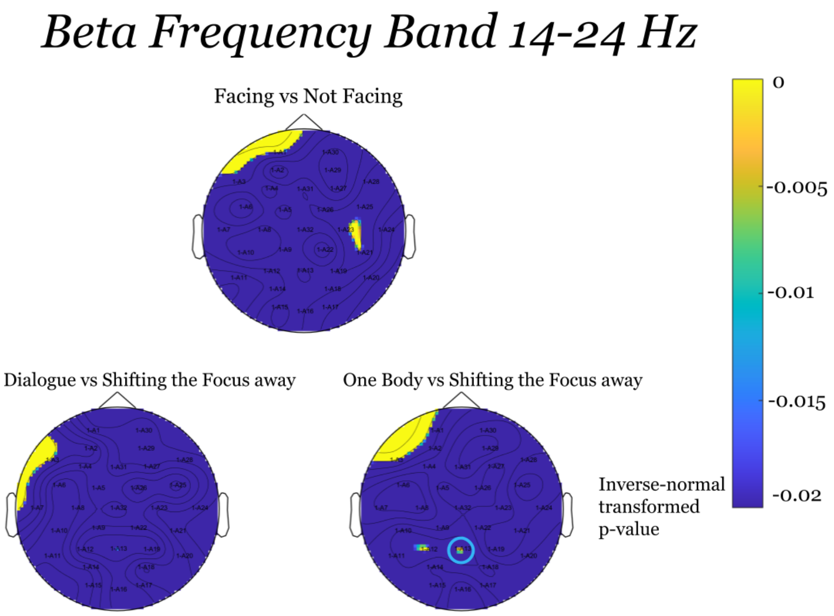

Figure 3.3: The effects of movement on the inter-brain synchrony at $p < .02$. Yellow means highly significant, while dark blue - no significance; circled in light blue – the channel which survived the multiple comparisons correction and indicates desynchronization while moving as one body as compared to shifting the focus away. The Dialogue-like movement condition suggests a decrease in inter-brain synchrony as well.

Table 3.6: Beta frequency band (14-24 Hz) mean phase-locking value (PLV) per channel.

Channel	Condition	Mean PLV
Fp1	Facing	0.2798
	Not Facing	0.2761
Pz	One Body	0.2730
	Dialogue	0.2761
	Shifting the Focus away	0.2814
P3	One Body	0.276
	Shifting the Focus away	0.2822
F7	One Body	0.2793
	Shifting the Focus away	0.2735
Pz	Dialogue	0.2784
	Shifting the Focus away	0.2782

synchrony in the theta band could be amplified by the link of this frequency band with the processing of facial emotions (Krause et al., 2000), in the facing case.

The increase in inter-brain phase synchronization in the alpha frequency band confirms the association of Tognoli, DeGuzman, and Kelso (2007) of this frequency with social coordination. This conclusion could explain the positive change in both the facing and not facing conditions. Previous findings on frontal alpha asymmetry within subjects associate the more alpha in the left hemisphere with motivation and positive emotions. One might argue since there is more inter-brain synchrony in the left hemisphere ($AF3$) as opposed to the right hemisphere (as Figure 3.2 suggests), the subjects might have felt similar positive emotions or were equally motivated (Coan and Allen, 2004; Harmon-Jones, Gable, and Peterson, 2010). Thus, the present study might point to a similar socioemotional pattern between subjects. Additionally, the positive change during the facing condition while moving synchronously could be a repercussion of the activation of the mirror neuron system as Pineda (2005) suggests. Since there are mixed opinions on this matter (Hobson and Bishop, 2016), further studies should focus more on determining the cause, considering none of the findings in this frequency band survive the multiple comparisons problem adjustment.

Codrons et al. (2014) found that joint arm movement lead to an increased autonomic (breathing rate) synchronization as compared to individual testing of the participants. The present research extends the previous study on synchronized breathing rate during synchronous movement, by illustrating a similar trend at the neuronal level. Hence, it may be concluded that indeed various synchronous movement leads to an increase in the physiological markers of human connectedness, like inter-brain synchrony and respiratory rhythm synchronization.

4.3 The effects of dancing in social versus nonsocial conditions

It was hypothesized that there would be a higher inter-brain phase synchrony when the participants would be connected both mentally and physically

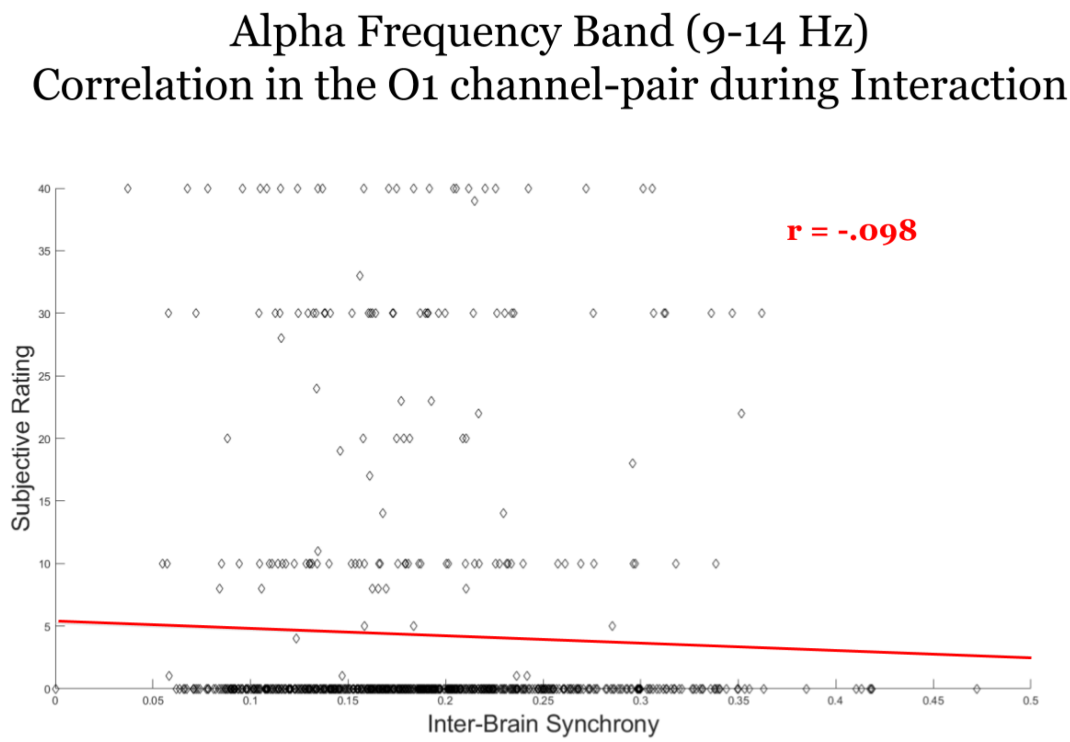

Figure 3.4: The inter-brain synchrony correlation of the O1 EEG channel-pair with the subjective ratings of connectedness in the Interaction behavioral variable. The red trend line indicates a weak negative correlation r(726) = -.098, p = .008. Take me back to text

(one body, dialogue) as opposed to non-socially (shifting the focus away to a prop, alone). The present study detected empirical evidence to support this assumption in the theta frequency band. When compared to the alone nonsocial condition, the activity increased in the theta band in the parieto-occipital ($PO4$) and right frontopolar ($Fp2$) areas. The observed increase in the $PO4$ channel-pair could be explained by a more intense visual stimulus and motor sensations, as compared to the alone condition, since the theta frequency is also associated with an increase in visual attention (Wang, Viswanathan, Lee, and Grafton, 2016) and cognitive control (Cavanagh and Frank, 2014). The increase in the $Fp2$ channel-pair could illustrate a trend of more emotional processing, as Knyazev, Slobodskoj-Plusnin, and Bocharov (2009); Krause et al. (2000) reported. Comparing the movement as one body with the nonsocial condition of shifting the focus away to a prop lead to an increase in the inter-brain synchrony in the parietal ($P4$), parieto-occipital ($PO4$) and the occipital (Oz) channel-pairs. Since the inter-brain synchrony increase in the centroparietal ($PO4$) area was robust enough to survive the multiple comparisons problem, this could be an indication of directing more attention to planning one's movements and predicting the timing of movements (Arnal and Giraud, 2012).

In the beta band (14-24 Hz) the results were quite miscellaneous. Foremost, it is worth to take into consideration that in this case some information might have been lost during data preprocessing because of down-sampling, as the beta frequency is the highest one analyzed.

As Figure 3.3 suggests, there is an increase in inter-brain synchrony in the frontal cortex ($F7$) when comparing the movement as one body with shifting the focus away to a prop. Conversely, the relatively strong difference in the left parietal cortex ($P3$) and the robust difference in inter-brain synchrony in the centroparietal cortex (Pz, surviving multiple comparison correction), point to desynchronization. Since the core focus of the study was on strategies capturing what would trigger the physiological markers of connectedness, one should keep in mind that some participants could experience mixed feelings while moving as one body as opposed to dancing with a prop. Some might had been more relaxed, while others more nervous; and the beta frequency is also slightly related to anxious thinking or active concentration (Farnsworth, 2019; Pavlidou et al., 2014). A possible explanation for the observed results might be that the participants had mixed mental representations and feelings, hence there was less synchronization caught between the dance partners. Nevertheless, further

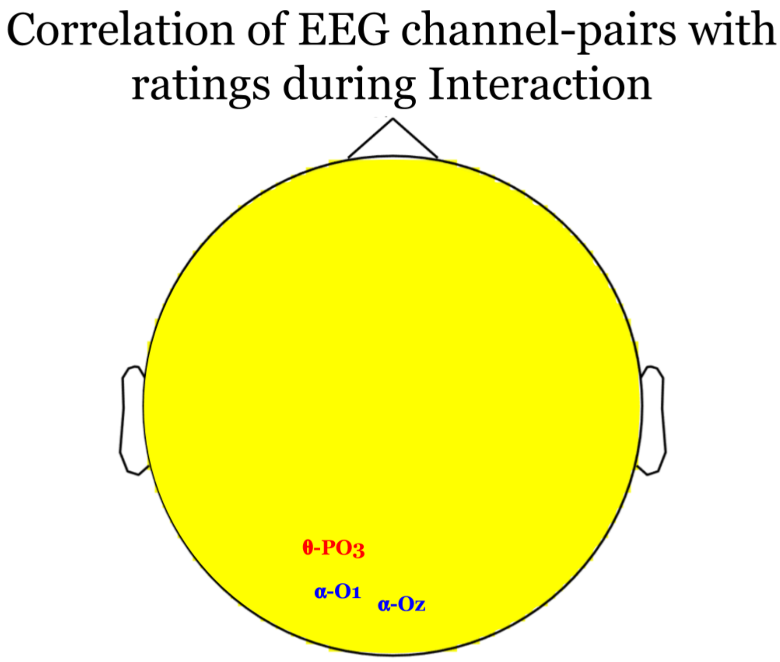

Figure 3.5: The EEG channel-pairs which showed the highest correlation with the subjective ratings during. In red - the PO3 channel pair with a positive correlation in the theta frequency band (7-9 Hz); in blue - the O1 and Oz channel-pairs with a negative correlation in the alpha frequency band (9-14 Hz). Take me back to text

studies with larger sample sizes are necessary to check whether these results are consistent.

4.4 Connecting physiological markers with subjective experience of connectedness

The attempt to connect the physiological marker of connectedness — inter-brain synchronization — with the subjective experience barely showed any links. A slight trend of positive correlation was detected in the parieto-occipital area ($PO3$) in the theta frequency band, which could suggest indeed this frequency might be related to human connectedness from a subjective point of view. The weak trend of the negative correlation found between the occipital areas and the ratings in the alpha frequency, could point to less perceived connectedness when the dancers were more visually focused. Yet there is a high chance this is only noise. To some extent this outcome was expected, considering the difficulty of analysing neuronal data. Since there is hardly any literature on this type of study, it could serve as a starting point for the future research. Another aspect worth to be taken into consideration is the EEG channel-pairs which were analyzed, were those identified in the experiment involving non-professional dancers. Some previous studies within individuals suggest professionals perceive dance differently than ordinary people (Poikonen, Toiviainen, and Tervaniemi, 2018a,b). Thus, it might had been a cleverer approach to first identify the EEG channel-pairs with the highest inter-brain synchrony for the professionals and correlate those with the subjective ratings.

4.5 Limitations

This research implemented a novel approach towards exploring the effects of moving in varying social conditions on human connectedness by looking at the neural correlates with EEG recordings. The previous studies of inter-brain synchrony during body movement focused on small finger or arm movements only (Dumas et al., 2010; Codrons et al., 2014), while in the present experiment the participants engaged in more holistic body movement. Moreover, those exploring the effects of dance on the brain (Poikonen et al., 2018a,b) conducted studies within subjects watching dance performances, while here the participants themselves are dancing and the analysis was carried out within and between subjects. Among the potential limitations of this tool for measuring electrical activity involves the limited spatial resolution of EEG. Considering the fact that the measurements are effectuated at the scalp level and the detected signal represents the summation of the electric field generated by a vast population of neurons, the intenser electrical activity can be detected by the neighboring electrodes as well. This in turn results in a less accurate detection of the signal location Schoffelen and Gross (2009). Moreover, since the EEG is quite sensitive to movement, the participants were more limited in expressing themselves. This implies, that there is a difference in how people move in their day-to-day life and in what the EEG measures. It is very likely that the weak correlations established between the inter-brain synchrony of the professional dancers and the subjective ratings were a direct consequence of the EEG sensitivity to movement. A possible solution which would allow the participants to move more naturally would be to use a wireless EEG system as Debener, Minow, Emkes, Gandras, and de Vos (2012) suggest, although this tool is still in an incipient phase of development.

Another limitation would be the potential presence of artifacts from eye movements, muscles (the participants were dancing!) and heartbeat. Even though these were thoughtfully eliminated via the independent component analysis, their potential impact on the present results cannot be neglected. The artifactual activity could lead to detecting evidence of increased or decreased inter-brain synchrony when actually it was not the case. Additionally, the start and the end of the EEG signal corresponding to the dance performance was extracted from video recordings made during the sessions. This could introduce some inaccuracies up to a couple of seconds in the timing of the analyzed EEG segments and the subjective ratings.

5 Conclusions

The present study suggests there is an increase in the inter-brain phase synchrony during facing conditions in the theta and beta frequency bands. There was also detected an increase in the theta and alpha frequency bands during the synchronous conditions and dancing as one body. On top of that, this study analyzed the effect of more holistic body movement on achieving human connectedness, as opposed to previous ones, which focused on arm movements (Codrons et al., 2014) or hand gestures (Nadel and Dumas, 2014).

The findings are in line with the previous discoveries, namely that the social condition which combined the most triggers (touch, moving simultaneously) of social connectedness — moving as one body — indicated the most substantial results. However, the observed data should be interpreted cautiously as most of the significantly found p-values at a threshold of 0.02 did not survive the multiple comparisons corrections. One should also not forget about the possible limitations which the sample size and the various differences of the individuals bring upon the aforementioned discrepancies. Additionally, it was investigated how the inter-brain synchrony in professional dancers related to the perceived connectedness from a subjective point of view. Unfortunately, the correlations were too weak for interpretation. Further studies could implement the suggestions and see whether indeed the physiological markers of connectedness correspond to the subjective experiences. Likewise, it would be intriguing to perform a longitudinal study to observe how inter-brain phase synchrony evolves over time in dancing people.

Moreover, since human connectedness is linked to feelings of empathy towards others (Cialdini, Brown, Lewis, Luce, and Neuberg, 1997), it would be interesting to compare joint movement with other already known techniques to increase human connectedness via empathy, e.g. via loving-kindness meditation (Hutcherson, Seppala, and Gross, 2008).

All things considered, the present research will hopefully help to develop more objective measures for the elusive experience of human connectedness.

References

R. Adolphs. The social brain: neural basis of social knowledge. *Annual review of psychology*, 60:693–716, 2009. doi:10.1146/annurev.psych.60.110707.163514.

M. Aickin and H. Gensler. Adjusting for multiple testing when reporting research results: the bonferroni vs holm methods. *American journal of public health*, 86(5):726–728, 1996. doi:https://doi.org/10.2105/AJPH.86.5.726.

L. H. Arnal and A.-L. Giraud. Cortical oscillations and sensory predictions. *Trends in Cognitive Sciences*, 16(7):390 – 398, 2012. ISSN 1364-6613. doi:doi.org/10.1016/j.tics.2012.05.003.

R.H. Baayen, D.J. Davidson, and D.M. Bates. Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, 59(4):390 – 412, 2008. ISSN 0749-596X. doi:https://doi.org/10.1016/j.jml.2007.12.005. Special Issue: Emerging Data Analysis.

J. F. Cavanagh and M.J. Frank. Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences*, 18(8):414 – 421, 2014. ISSN 1364-6613. doi:10.1016/j.tics.2014.04.012.

SY Chen, Z Feng, and X Yi. A general introduction to adjustment for multiple comparisons, 2017.

R. B. Cialdini, S. L. Brown, B. P. Lewis, C. Luce, and S. L. Neuberg. Reinterpreting the empathy–altruism relationship: When one into one equals oneness. *Journal of Personality and Social Psychology*, 73(3):481 – 494, 1997. ISSN 0022-3514.

J. A. Coan and J.J.B. Allen. Frontal eeg asymmetry as a moderator and mediator of emotion. *Biological Psychology*, 67(1):7 – 50, 2004. ISSN 0301-0511. doi:https://doi.org/10.1016/j.biopsycho.2004.03.002. Frontal EEG Asymmetry, Emotion, and Psychopathology.

E. Codrons, N. F. Bernardi, M. Vandoni, and L. Bernardi. Spontaneous group synchronization of movements and respiratory rhythms. *PLOS ONE*, 9(9):1–10, 09 2014. doi:10.1371/journal.pone.0107538.

S. Debener, F. Minow, R. Emkes, K. Gandras, and M. de Vos. How about taking a low-cost, small, and wireless eeg for a walk? *Psychophysiology*, 49(11):1617–1621, 2012. doi:10.1111/j.1469-8986.2012.01471.x.

G. Dumas, J. Nadel, R. Soussignan, J. Martinerie, and L. Garnero. Inter-brain synchronization during social interaction. *PLOS ONE*, 5(8):1–10, 08 2010. doi:10.1371/journal.pone.0012166.

B. Farnsworth. Eeg (electroencephalography): The complete pocket guide, Aug 2019. URL `https://imotions.com/blog/eeg/`.

T. F. Field, B. Healy, and W. G. LeBlanc. Sharing and synchrony of behavior states and heart rate in nondepressed versus depressed mother-infant interactions. *Infant Behavior and Development*, 12(3):357 – 376, 1989. ISSN 0163-6383. doi:https://doi.org/10.1016/0163-6383(89)90044-1.

O. Friard and M. Gamba. Boris: a free, versatile open-source event-logging software for video/audio coding and live observations. *Methods in Ecology and Evolution*, 7(11):1325–1330, 2016. doi:10.1111/2041-210X.12584.

M. Gilbert. *On social facts*. Princeton University Press, 1992.

P. Goldstein, I. Weissman-Fogel, G. Dumas, and S. G. Shamay-Tsoory. Brain-to-brain coupling during handholding is associated with pain reduction. *Proceedings of the National Academy of Sciences*, 115(11):E2528–E2537, 2018. ISSN 0027-8424. doi:10.1073/pnas.1703643115.

B. M.K. Hagerty, J. Lynch-Sauer, K. L. Patusky, and M. Bouwsema. An emerging theory of human relatedness. *Image: the Journal of Nursing Scholarship*, 25(4):291–296, 1993. doi:10.1111/j.1547-5069.1993.tb00262.x. URL `https://sigmapubs.onlinelibrary.wiley.com/doi/abs/10.1111/j.1547-5069.1993.tb00262.x`.

E. Harmon-Jones, P. A. Gable, and C. K. Peterson. The role of asymmetric frontal cortical activity in emotion-related phenomena: A review and update. *Biological Psychology*, 84(3):451 – 462, 2010. ISSN 0301-0511. doi:https://doi.org/10.1016/j.biopsycho.2009.08.010. The biopsychology of emotion: Current theoretical and empirical perspectives.

H. M. Hobson and D. V. M. Bishop. Mu suppression – a good measure of the human mirror neuron system? *Cortex*, 82:290 – 310, 2016. ISSN 0010-9452. doi:10.1016/j.cortex.2016.03.019.

T. Honghong et al. Interpersonal brain synchronization in the right temporo-parietal junction during face-to-face economic exchange. *Social Cognitive and Affective Neuroscience*, 11(1):23–32, 07 2015. ISSN 1749-5016. doi:10.1093/scan/nsv092.

C. A. Hutcherson, E. M. Seppala, and J. J. Gross. Loving-kindness meditation increases social connectedness. *Emotion*, 8(5):720 – 724, 2008. ISSN 1528-3542.

J. Jiang et al. Neural synchronization during face-to-face communication. *Journal of Neuroscience*, 32(45):16064–16069, 2012. ISSN 0270-6474. doi:10.1523/JNEUROSCI.2926-12.2012.

M. J. Kahana. The cognitive correlates of human brain oscillations. *Journal of Neuroscience*, 26(6):1669–1672, 2006. ISSN 0270-6474. doi:10.1523/JNEUROSCI.3737-05c.2006.

G.G. Knyazev, J.Y. Slobodskoj-Plusnin, and A.V. Bocharov. Event-related delta and theta synchronization during explicit and implicit emotion processing. *Neuroscience*, 164 (4):1588 – 1600, 2009. ISSN 0306-4522. doi:10.1016/j.neuroscience.2009.09.057.

C. M. Krause, V. Viemerö, A. Rosenqvist, L. Sillanmäki, and T. Åström. Relative electroencephalographic desynchronization and synchronization in humans to emotional film content: an analysis of the 4–6, 6–8, 8–10 and 10–12 hz frequency bands. *Neuroscience Letters*, 286(1):9 – 12, 2000. ISSN 0304-3940. doi:10.1016/S0304-3940(00)01092-2.

J.-P. Lachaux, E. Rodriguez, J. Martinerie, and F. J. Varela. Measuring phase synchrony in brain signals. *Human brain mapping*, 8(4):194–208, 1999. doi:https://doi.org/10.1002/(SICI)1097-0193(1999)8:4<194::AID-HBM4>3.0.CO;2-C.

Eric Lowet, Mark J. Roberts, Pietro Bonizzi, Joël Karel, and Peter De Weerd. Quantifying neural oscillatory synchronization: A comparison between spectral coherence and phase-locking value approaches. *PLOS ONE*, 11(1):1–37, 01 2016. doi:10.1371/journal.pone.0146443.

K. L. Marsh, M. J. Richardson, and R. C. Schmidt. Social connection through joint action and interpersonal coordination. *Topics in Cognitive Science*, 1(2):320–339, 2009. doi:https://doi.org/10.1111/j.1756-8765.2009.01022.x.

J. G. Miller et al. Inter-brain synchrony in mother-child dyads during cooperation: An fnirs hyperscanning study. *Neuropsychologia*, 124:117 – 124, 2019. ISSN 0028-3932. doi:https://doi.org/10.1016/j.neuropsychologia.2018.12.021.

V. Müller and U. Lindenberger. Cardiac and respiratory patterns synchronize between persons during choir singing. *PLOS ONE*, 6(9):1–15, 09 2011. doi:10.1371/journal.pone.0024893.

J. Nadel and G. Dumas. The interacting body: Intra- and interindividual processes during imitation. *Journal of Cognitive Education and Psychology*, 13(2):163–175, 2014. doi:10.1891/1945-8959.13.2.163.

R. O'Neill and G. B. Wetherill. The present state of multiple comparison methods. *Journal of the Royal Statistical Society. Series B (Methodological)*, 33(2):218–250, 1971. ISSN 00359246. URL `http://www.jstor.org/stable/2985004`.

R. Oostenveld. How does mtmconvol work?, 2020. URL `http://www.fieldtriptoolbox.org/faq/mtmconvol/`.

R. Oostenveld, P. Fries, E. Maris, and J.-M. Schoffelen. Fieldtrip: open source software for advanced analysis of meg, eeg, and invasive electrophysiological data. *Computational intelligence and neuroscience*, 2011, 2011. doi:https://doi.org/10.1155/2011/156869.

A. Pavlidou, A. Schnitzler, and J. Lange. Beta oscillations and their functional role in movement perception. *Translational Neuroscience*, 5(4):286–292, 2014. doi:10.2478/s13380-014-0236-4.

J.A. Pineda. The functional significance of mu rhythms: Translating "seeing" and "hearing" into "doing". *Brain Research Reviews*, 50(1):57 – 68, 2005. ISSN 0165-0173. doi:10.1016/j.brainresrev.2005.04.005.

W. B. Plotkin and R. Cohen. Occipital alpha and the attributes of the "alpha experience". *Psychophysiology*, 13(1):16–21, 1976. doi:10.1111/j.1469-8986.1976.tb03329.x.

H. Poikonen, P. Toiviainen, and M. Tervaniemi. Naturalistic music and dance: Cortical phase synchrony in musicians and dancers. *PLOS ONE*, 13(4):1–18, 04 2018a. doi:10.1371/journal.pone.0196065. URL `https://doi.org/10.1371/journal.pone.0196065`.

H. Poikonen, P. Toiviainen, and M. Tervaniemi. Dance on cortex: enhanced theta synchrony in experts when watching a dance piece. *European Journal of Neuroscience*, 47(5):433–445, 2018b. doi:10.1111/ejn.13838.

B. J. Roach and D. H. Mathalon. Event-Related EEG Time-Frequency Analysis: An Overview of Measures and An Analysis of Early Gamma Band Phase Locking in Schizophrenia. *Schizophrenia Bulletin*, 34(5):907–926, 08 2008. ISSN 0586-7614. doi:10.1093/schbul/sbn093.

J.-M. Schoffelen and J. Gross. Source connectivity analysis with meg and eeg. *Human Brain Mapping*, 30(6):1857–1865, 2009. doi:10.1002/hbm.20745.

J. R. Searle, S. Willis, et al. *The construction of social reality.* Simon and Schuster, 1995.

J. Tognoli, E.and Lagarde, G. C. DeGuzman, and J. A. S. Kelso. The phi complex as a neuromarker of human social coordination. *Proceedings of the National Academy of Sciences*, 104(19):8190–8195, 2007. ISSN 0027-8424. doi:10.1073/pnas.0611453104.

B. Tunçgenç and E. Cohen. Movement synchrony forges social bonds across group divides. *Frontiers in Psychology*, 7:782, 2016. ISSN 1664-1078. doi:10.3389/fpsyg.2016.00782.

P. Van Leeuwen et al. Influence of paced maternal breathing on fetal–maternal heart rate coordination. *Proceedings of the National Academy of Sciences*, 106(33):13661–13666, 2009. ISSN 0027-8424. doi:10.1073/pnas.0901049106.

M. K. van Vugt, P. B. Sederberg, and M. J. Kahana. Comparison of spectral analysis methods for characterizing brain oscillations. *Journal of neuroscience methods*, 162(1-2):49–63, 2007. doi:https://doi.org/10.1016/j.jneumeth.2006.12.004.

M. K. van Vugt et al. Inter-brain synchronization in the practice of tibetan monastic debate. *Mindfulness*, pages 1–15, 2020. doi:https://doi.org/10.1007/s12671-020-01338-1.

W. Wang, S. Viswanathan, T. Lee, and S. T. Grafton. Coupling between theta oscillations and cognitive control network during cross-modal visual and auditory attention: Supramodal vs modality-specific mechanisms. *PLOS ONE*, 11(7):1–16, 07 2016. doi:10.1371/journal.pone.0158465.