Computational cognitive science
Department of Artificial Intelligence

Master's Thesis
January, 2022

Is there a universal way to connect?
Altering inter-brain synchrony by inducing social connectedness through movement

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Abstract

Studies have shown that when people are dancing together, they feel more socially connected. We were wondering whether this connection is visible on a neural basis by brains that synchronize. In this thesis, the relationship between inter-brain synchrony and feeling socially connected through movement is investigated. A performance during the Moving Futures Festival where two professional dancers explored various ways to connect, laid the foundation for the laboratory experiment. In this experiment, dyads moved in several social and nonsocial conditions while being hyperscanned by electroencephalography (EEG). The mean phase-locking value and imaginary coherence were used to compute inter-brain synchrony. Besides recording brain activity, the participants also reported how connected they felt in each condition. The results showed that the dyads experienced feeling more connected in most of the social conditions compared to the nonsocial conditions. In addition, we found significant inter-brain synchrony in various brain areas in the theta and alpha oscillations but not for the oscillations in the beta band. We predicted to see more inter-brain synchrony in the social conditions compared to the nonsocial conditions. We found conditions where this was indeed the case. However, we also found conditions where there was more inter-brain synchrony in the nonsocial conditions compared to the social conditions. Furthermore, we discovered that inter-brain synchrony was affected by several factors, such as gender and the relationship of the dyads. The trends uncovered in the laboratory experiment did not seem to uphold for the inter-brain synchrony of the two professional dancers. The results suggest there exist ways of moving together that make people feel socially connected. Moreover, there is significant inter-brain synchrony during movement in various conditions. However, our results did not expose a significant relationship between the subjective experience of social connectedness and inter-brain synchrony.

1 Introduction

Social connectedness is feeling connected to another person, group or environment. There is a consensus in the literature that feeling socially connected benefits both the mental and physical well-being of humans. Take the research by Ashida and Heaney (2008). According to Ashida and Heaney, perceived social connectedness is beneficial for the well-being of older adults. They argue that older adults should make efforts towards developing friends. Developing friends would allow them to feel more socially connected and, as a consequence, it will improve their overall well-being. However, the opposite can also be said to be true. The absence of feeling socially connected can negatively impact both the physical and mental state of humans. For example, Fatima, Niazi, and Ghayas (2017) showed that social connectedness negatively predicted social anxiety. Meaning that low levels of social connectedness can lead to greater signs of social anxiety. Social anxiety impacts, besides mental health, also physical well-being. Strine, Chapman, Kobau, Balluz, and Mokdad (2004) demonstrated that when people report having mental health issues, of which anxiety was one of them, there is a reduced health-related quality of life and health behaviours. Thus, being able to induce the feeling of social connectedness could be beneficial to one's mental and physical health.

There are ways to bring about social connectedness besides interacting with others. Hutcherson, Seppala, and Gross (2008) demonstrated that a short loving-kindness meditation exercise increased the feeling of social connectedness between strangers. In addition, moving or dancing together also appears to increase the feeling of social connectedness. For example, dancing can encourage social closeness between strangers (Tarr, Launay, & Dunbar, 2016). Another study done by Tarr strengthens the connection between dancing and social closeness (Tarr, Launay, Cohen, & Dunbar, 2015). However, in this study, Tarr et al. explicitly mention synchronized movement. In an earlier study, Tarr, Launay, and Dunbar (2014) explored evidence that synchronization elicits social connectedness, or as they called it social bonding. Tarr et al. discuss several studies which address various types of synchronization and social bonding. One of these studies is by Reddish, Fischer, and Bulbulia (2013). Reddish et al. showed that groups reported feeling more socially united when being engaged in synchronized movement compared to moving asynchronously. This raises the question, are there other ways of moving or dancing together that makes people feel socially connected?

For investigating whether people feel more socially connected, an apparent way to measure this is by asking whether they feel socially connected. For example, Fatima et al. (2017) used questionnaires to measure social connectedness using a social connectedness scale. Even though questionnaires and self-reports are reliable measures, they are still subjective measures. Is there perhaps a physiological or neurological basis underlying the feeling of social connectedness? The research by McCraty (2017), and the ones he discusses, suggest that various physiological markers are underlying social interaction. McCraty describes it as research where varying aspects of social interaction depend on "spontaneous synchronization of various physiological rhythms between individuals" (McCraty, 2017). One of the physiological rhythms he highlights is heart rate variability (HRV). McCraty even argues that prosocial behaviour will increase when groups are trained to increase heart rhythm synchronization. Besides the HRV, McCraty (2017) mentions brain-to-brain synchrony as a physical indicator for, in his words, social coherence.

Valencia and Froese (2020) support this claim. They examined research supporting the claim that inter-brain synchrony is an indicator for social interaction. Inter-brain synchrony occurs when brain activity between two or more people becomes synchronized. A few examples of social interaction Valencia and Froese (2020) mention are coordination (Mu, Guo, & Han, 2016; Mu, Han, & Gelfand, 2017), cooperation (Hu et al., 2018), joint action (Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010; Sänger, Müller, & Lindenberger, 2012) and joint attention (Szymanski et al., 2017). During these different aspects of social interaction, inter-brain synchrony was discovered. Valencia and Froese (2020) also report that inter-brain synchrony has been linked with subjective reports of social connectedness. However, according to Balconi and Vanutelli (2017), as cited by Valencia and Froese (2020), studies investigating inter-brain synchrony and the subjective reports of social connectedness did not explicitly account for the personal experience of the participants. One study that accounted for this was Bevilacqua et al. (2019). Their objective was to investigate the dynamics between students and their teacher and how that affected learning. Bevilacqua et al. (2019) demonstrated that the closeness between student and teacher predicted inter-brain synchrony. Namely, students that reported feeling more socially connected to the teacher also showed more inter-brain synchrony with the teacher.

So, there is evidence that (synchronous) dancing and movement can lead to the feeling of connectedness. However, if this only accounts for synchronous movement or whether there are other ways of dancing and moving that can lead to social connectedness is yet to be determined. The literature presents several ways of measuring and quantifying social connectedness. If inter-brain synchrony is such a measure to determine whether dancing can elicit social connectedness remains to be seen. In addition, besides the study by Bevilacqua et al. (2019), there is no substantial evidence on how inter-brain synchrony connects to the subjective experience of social closeness. These are the main objectives of this thesis. In the next section, the research questions will be presented on how to address these objectives.

1.1 Research Question

We know that various ways bring about the feeling of connectedness, one of which is, joined movement or dancing. We also know that there is a connection between social interaction and inter-brain synchrony. Joint action is an example of social interaction that increases inter-brain synchrony. Synchronized movement and dancing led to feeling connected compared to moving asynchronously. We do not know what other types of movement or dancing can lead to this feeling of connectedness. Furthermore, whether there is a link between the subjective experience of connectedness induced by movement and inter-brain synchrony is unclear. We summarized the objectives into the following two research questions:

1. Can dance-like movements induce the feeling of social connectedness?
2. Is inter-brain synchrony a measure for the subjective report of social connectedness?

We propose that by looking at inter-brain synchrony together with subjective reports, we could find out if and what type of movements could bring about the feeling of social connectedness. In the Theoretical Framework, we discuss research about inter-brain synchrony during social interactions. In addition, we address ways to measure brain activity and how to quantify inter-brain synchrony.

2 Theoretical Framework

Various techniques can be used for recording brain activity to determine whether two or more brains are connected. Functional magnetic resonance imaging (fMRI) (Stephens, Silbert, & Hasson, 2010), functional near-infrared spectroscopy (fNIRS) (Liu, Duan, Dai, Pelowski, & Zhu, 2021), electroencephalography (EEG) (Dumas et al., 2010) and magnetoencephalography (MEG) (Bourguignon et al., 2013) are examples of hyperscanning techniques used to study the effects of social interaction in multiple brains. Even though fMRI is high in spatial resolution, subjects are restricted in their movements. According to Nam, Choo, Huang, and Park (2020), 47% of the hyperscanning studies researching inter-brain synchrony during social interactions used MEG/EEG. Nam et al. reviewed over 100 studies that were published since 2002. Even though MEG is spatially more precise than EEG, MEG does limit mobility similar to fMRI. Besides the fact that EEG has a high temporal resolution, it is also the most practical technique for recording brain activity of multiple brains while subjects are engaged in movement. In the next section, research about inter-brain synchrony during social interaction will be discussed. Since EEG recorded brain activity is used in this thesis, we will address, foremost, research that involves EEG recorded brain activity.

2.1 Inter-brain synchrony in social interaction

In the literature, various terms are used to denote the synchronization of brains. Liu et al. (2021) called it interpersonal synchrony, McCraty (2017) called it brain-to-brain synchrony, Dikker et al. (2021) called it inter-brain coupling, and Dumas et al. (2010) called it inter-brain synchrony. For the remainder of this thesis, we will use the term inter-brain synchrony similar to Dumas et al. (2010). In addition, throughout this thesis, the term 'social connectedness' will refer to feeling connected towards another person.

The review by Valencia and Froese (2020) discusses numerous studies that have used EEG when studying inter-brain synchrony during social interaction. One of the studies is Dumas et al. (2010) who, recorded dual-EEG activity between dyads to investigate inter-brain synchrony in social interaction. The dual-EEG technique allows brain activity from two people to be recorded simultaneously. The subjects were performing various meaningless hand movements that had to be copied by the partner while the brain activity of both subjects was recorded at the same time. Dumas et al. found that inter-brain synchronization corresponded with interactional synchrony. Interactional synchrony implies the mirroring of behaviour and movement when people interact. The discovered brain regions and frequencies bands involved in inter-brain synchronization are; the right parietal regions in the alpha-mu frequency band, the central and parieto-occipital regions in the beta frequency band, and fronto-central and parietal regions in the gamma frequency bands. Dumas et al. (2010) showed with their research that different brain areas in various frequency bands can synchronize between two people during joint hand movement.

Dikker et al. (2021) also used EEG to record brain activity from pairs, however, their objective was to take a more naturalistic approach and go outside the laboratory. They investigated inter-brain synchrony in face-to-face interaction. Dikker et al. gathered EEG-data at festivals and museums. This procedure led to a large and diverse subject pool. Dikker et al. (2021) found that the pairs that knew each other well showed more inter-brain synchrony compared to pairs who did not know each other. Moreover, they argue that their findings support an account where joint action and shared engagement drive coupled neural activity. The inter-brain synchrony was, most notably, found in the beta and alpha oscillations. Dikker et al. (2021) did not specify what brain areas were involved in the inter-brain couplings.

Sänger et al. (2012) used EEG to investigate the effect of joint action and music-making on inter-brain synchrony. They looked at coordinated behaviour during guitar duets. The subjects did not perform the music performance in unison but used leader and follower roles. Besides the different roles, the guitarists played in two different voices. To account for the possibility that inter-brain synchrony between two or more people engaged in joint action is due to similarities in visual input and motor output (Lindenberger, Li, Gruber, & Müller, 2009). Sänger et al. (2012) found that between-brain phase-coherence connection strengths were enhanced at frontal and central electrodes in the delta and theta frequency bands during periods that put high demands on musical coordination.

Dunbar, Kaskatis, MacDonald, and Barra (2012) found that dancing while listening to music heightens the pain threshold. In line with this finding, Goldstein, Weissman-Fogel, Dumas, and Shamay-Tsoory (2018) investigated whether hand-holding while administrating pain is associated with pain reduction. Their results showed that interpersonal touch during pain did not only lead to pain reduction but also inter-brain synchrony between the observer and the target of the pain. According to Goldstein et al., their results suggest that social interactions are associated with inter-brain synchrony in the alpha band. They especially found a network that consisted of couplings between the central regions of the pain target's brains to the right hemisphere of the observer's brains. It has to be noted that the dyads in Goldstein et al. (2018) research were heterosexual romantic couples and pain was only administered to the females. Thus, these results do not say anything about the networks between male-to-female brains.

Pan, Cheng, Zhang, Li, and Hu (2017) on the other hand, did investigate female-to-male and male-to-female inter-brain synchrony. They investigated whether a cooperation task between lovers affected inter-brain synchrony. Pan et al. (2017) fNIRS results showed that there was only inter-brain synchrony between lover dyads and not between friends or strangers. In addition, for the lover dyads, the direction of the inter-brain synchrony was stronger from females to males compared to males to females. Pan et al. (2017) note that the lovers were all undergraduate students and that the relationships were only in the early stages. Instead of just looking at whether or not people are in a relationship, also the length, amongst others, should be taken into account. This is in line with the findings of Dikker et al. (2021), who found that the relationship between the dyads affected inter-brain synchrony. These findings suggest that the gender and the relationship between the dyads affect inter-brain synchrony.

2.2 Frequency bands of interest

The studies mentioned in the previous section are examples of research that investigated inter-brain synchrony during joint action and social interaction between dyads. The interesting aspect is that Dikker et al. (2021); Dumas et al. (2010); Goldstein et al. (2018); Sänger et al. (2012) and others, all found varying brain regions and frequency bands involved. For this thesis, we are interested in whether inter-brain synchrony during movement is associated with the feeling of social connectedness. According to Dumas et al. (2010), as cited by Goldstein et al. (2018), the alpha band is the most robust frequency band for inter-brain synchrony. Besides Dumas et al. (2010), also Dikker et al. (2021); Hu et al. (2018); Mu et al. (2016) found inter-brain synchrony in the alpha band during social interaction.

In addition, Hu et al. (2018) also found the frontal-central region to synchronize in the theta band during a cooperation game. Furthermore, the frontal and central regions showed inter-brain synchrony in the theta band during guitar playing duets (Sänger et al., 2012).

Aside from the alpha and theta bands, various studies suggested the possible involvement of the beta band in inter-brain synchrony during social interaction. For instance, Dumas et al. (2010) found significant synchronized oscillations in the central and parieto-occipital regions in the beta band during joint action. Finally, during face-to-face interaction, the inter-brain synchrony was, next to the alpha band, most notably found in the beta oscillations (Dikker et al., 2021).

Bevilacqua et al. (2019) showed the importance of the relationship between the subjective experience of social closeness and inter-brain synchrony. They reported calculating the coherence for the frequencies in the range of 1 to 20 Hz. However, when describing their findings, whether the inter-brain synchrony occurred in a specific frequency band was not mentioned. The frequency range roughly covers the alpha, theta and even a part of the beta frequency band. Based on these findings, we believe that the alpha, theta and beta frequency bands are to be of interest in answering our research questions.

2.3 Quantifying inter-brain synchrony

Various methods have been created and tested to quantify inter-brain synchrony in EEG recorded brain activity. Phase synchrony measures are a commonly used method to determine functional connectivity. According to Yoshinaga et al. (2020), there is no consensus on which phase synchrony measure to use in a given experimental paradigm. Yoshinaga et al. (2020) compared four phase synchronization measures to detect stimulus-induced functional connectivity in human MEG and simulated data. They found that imaginary coherence was the most sensitive measure in detecting stimulus-induced functional connectivity. Yoshinaga et al. argue that the better performance is due to amplitude weighting. However, Yoshinaga et al. (2020) used the imaginary coherence, amongst others, to determine functional connectivity within a brain and not between brains. Dikker et al. (2021) used imaginary coherence to quantify inter-brain synchrony besides using the projected power correlation. Both measures found inter-brain synchrony in different frequencies. Where Yoshinaga et al. (2020) argued for finding the best measure for a specific experimental paradigm, Dikker et al. (2021) show that multiple measures can yield different results. Instead of using one measure over another, various measures could give more insightful results.

The most used method in the studies mentioned earlier is the phase-locking value (Dumas et al., 2010; Hu et al., 2018; Mu et al., 2016, 2017). Besides the phase-locking value, Sänger et al. (2012) also used the inter-brain phase coherence measure. The studies that did not use the phase-locking value are Goldstein et al. (2018) who used circular correlation coefficient, and Bevilacqua et al. (2019) who, used total interdependence. Even though the phase-locking value is an often-used measure, the other methods do support the claim by Yoshinaga et al. (2020) that there is no consensus on what measure to use to determine functional connectivity, whether this is within or between brains.

Preliminary results from Regus (2020), which used EEG data that will also be used for this thesis, suggested that there is an increase in the inter-brain phase synchrony between dyads in various conditions for the theta, beta and alpha frequency bands. However, most of the findings did not survive the multiple comparison correction.

So, there is no consensus in the literature about a measure that trumps all others. In addition, Dikker et al. (2021) showed that two different inter-brain synchrony measures can yield different results. Even though most of Regus (2020) findings did not survive the correction for the multiple comparison problem. We believe that we could improve quantifying inter-brain synchrony by using different methods. In the following sections, we elaborate on the method we opted for.

2.3.1 Phase-locking value

The previous section showed that the phase-locking value (PLV) is a well-studied measure for quantifying inter-brain synchrony. The PLV is a measure to determine the phase synchrony between two time series and was introduced by Lachaux, Rodriguez, Martinerie, and Varela (1999). According to Nam et al. (2020), Tognoli, Lagarde, DeGuzman, and Kelso (2007) were the first to use the PLV during an EEG hyperscanning study. However, Tognoli et al. (2007) did not directly test for inter-brain synchrony during social coordination, as stated by Dumas et al. (2010).

Even though the PLV is a widely used method, it is sensitive to volume conduction (Lachaux et al., 1999). Volume conduction means that activity that is recorded in multiple electrodes originates from the same source but is conducted through biological tissue and ends up at multiple electrodes. Volume conduction is not just an issue that the PLV is sensitive to. It is an issue that arises with EEG and MEG recorded brain activity. Nolte et al. (2004) argue that they found a reliable method for quantifying inter-brain synchrony that is not sensitive to detecting false connectivity due to volume conduction. This method uses the imaginary part of coherence to determine inter-brain synchrony. Nolte et al. (2004) conclude that it is possible to detect inter-brain synchrony during movement from EEG data using this measure. How the imaginary coherence corrects for volume conduction will be discussed in the next section.

2.3.2 The imaginary part of coherence

Dikker et al. (2021) used imaginary coherence to determine inter-brain synchrony which was based on the work by Nolte et al. (2004). The imaginary coherence is also a phase synchronization measure and the workings of the imaginary coherence is in the name itself. It takes the imaginary part of the coherence between two time series which represents the lagged interactions. The instantaneous interactions are represented by the real part and thus ignored by imaginary coherence. Nolte et al. (2004) argue that lagged phases do not arise from volume conduction and therefore believe the imaginary coherence only shows true synchronization. Nolte et al. believes that volume conduction leads to instantaneous interaction. Meaning that the phases are similar or close to similar. Vinck, Oostenveld, van Wingerden, Battaglia, and Pennartz (2011) described the working of the imaginary coherence being insensitive to volume conduction as follows; conducted electrical activation has a negligible time delay in surrounding electrodes that originated from a single source. The disadvantage with this is that the imaginary coherence does not detect coherence if two time series are in phase opposition or in phase. Nolte et al. do note that in their words; ”it is likely that our approach misses parts and in the worst case all of the brain interaction” (Nolte et al., 2004). But this also implies that once a non-vanishing imaginary part is detected, then this can almost immediately be interpreted as true brain synchronization.

Ignoring the real part of coherence is the strength of the imaginary coherence as it prevents synchrony to be labelled as true synchronization when in fact it is instantaneous synchronization caused by, for example, noise. However, the fact that it ignores the real part is also its weakness. When there are true zero-phase lag differences between brains these are ignored. Moreover, when there are true but very small phase lags that are close to zero then these are also ignored. So, where the PLV would most likely produce type I errors, the imaginary coherence will most likely produce type II errors.

3 Methods

3.1 Laboratory experiment

3.1.1 Participants

A total of 60 volunteers participated in the study of whom 31 were female and 29 male (ages 18-35). The study was advertised on Facebook and by word of mouth. This resulted in a group of participants with varying backgrounds, i.e., none had a professional dancing background. The participants were divided into pairs, dyads. The data of five dyads were removed due to noisy data, leaving data from 25 dyads. For one condition, data from 6 dyads was missing. The relationship between the dyads varied; colleagues, friends, strangers, sisters and spouses. Also, the genders of the dyads varied, 32% of the dyads had the same gender (50% male-male and 50% female-female). All participants signed an informed consent form before the start of the experiment. Participants received compensation of €16 euros. The experiment was conducted in accordance with the Declaration of Helsinki.

3.1.2 Equipment

The dyads were invited to move in various conditions at the rhythm of a metronome beat of 80 bpm. During the experiment, each dyad was being hyperscanned, their brain activity was being recorded at the same time with electroencephalography (EEG). The equipment that was used was the BioSemi with Daisy-chain technology. The benefit of the Daisy-chain technology is that it allows to record the brain activity of multiple brains at the same time without creating interference. Each condition lasted two minutes and activity was recorded from 32 electrodes and six facial electrodes. The 32 electrodes were placed in accordance with the internationally accepted 10-20 system. The placement of the facial electrodes was as follows; two on the mastoids, one below and one above an eye and one on the outside of each eye. The electrodes around the eyes are placed there to catch eye-movement artefacts (e.g. blinking). The mastoid electrodes are used for referencing. The sampling rate was 512 Hz and the impedance was below 40 kΩ.

3.1.3 Design

The conditions were based on the performance of Random Collision, a contemporary Dance company, during the Moving Futures festival 2019 and literature. More about the performance of Random Collision will be provided in Section 3.2. To investigate the relationship between movement and inter-brain synchrony, the dyads had to move in various conditions. These conditions also consider possible aspects that may affect inter-brain synchrony such as moving in synchrony (Reddish et al., 2013), touch (Goldstein et al., 2018) or whether the dyads are facing each other (Dikker et al., 2021). The conditions can be divided into social and nonsocial conditions. The social and nonsocial conditions allow us to investigate whether there is more synchrony in the social conditions compared to the nonsocial conditions. The social conditions are conditions where literature has suggested that there is inter-brain synchrony. First, the **facing** condition where the participants in a dyad faced each other and either danced **synchronously** or **asynchronously**. Second, the dyads again had to move either **synchronously** or **asynchronously**. However, this time the dyads were not facing each other. In the condition where the dyads were not facing each other, the metronome was crucial for them to still be able to move in synchrony. The next social condition is the condition where the dyads had to answer each other movements as if they were in a **dialogue** with each other. The partners moved alternately. The last social condition is the **one-body** condition in which the dyads had to move as if they were sharing a single body. The following nonsocial condition is that participants had to dance **alone**. The last nonsocial condition is where the dyads had to dance with a prop. In this condition, the dyads shifted their focus to the prop, away from their partner. This condition is called **shift-of-focus**. Each dyad performed all the conditions. An overview of the conditions and to which conditions they are going to be compared in the statistical analysis are in Table 1. The **dialogue** condition was not compared to the **alone** condition since Regus (2020) did not find significant results when comparing these conditions. Hence, we decided to leave out this condition pair for comparison. There was no choreography linked to the conditions. So, the dyads could move according to their interpretation of the conditions.

Table 1: Overview of the social and nonsocial conditions to be compared

Conditions		
Facing	vs.	Not facing
Synchronous	vs.	Asynchronous
Dialogue	vs.	Shift-of-Focus
One-Body	vs.	Shift-of-Focus
One-Body	vs.	Alone

3.1.4 Procedure

After the EEG cap and the face electrodes were attached, the dyads were invited to engage in 2-minute sections of movement in the various conditions explained in section 3.1.3. To reduce the probability of movement artefacts, participants were asked to restrict their movements to arm and hand movements.

Every participant was asked how connected they felt to the other person during the different conditions. Each participant gave a subjective rating on a scale of 0 to 10 for both mental and physical connection separately. The 0 indicated not feeling connected towards the other person, whereas the 10 indicated the feeling of complete connectedness. The experiment and data collection was conducted in Groningen, in the Netherlands.

3.1.5 Data processing and analysis

EEG preprocessing

The EEG data were preprocessed using the Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) in Matlab. First, we applied a low-pass band filter from 0.5 to 45 Hz to the EEG data to remove high-frequency muscle activity. Next, the data were resampled to 256 Hz. After that, for each participant separately, an independent component analysis (ICA) was done. With visual inspection artifactual activity (e.g. eye movements, blink, heartbeat and muscle activity) was identified and then removed with ICA. At first, the Cz electrode was used as the reference signal but the data were re-referenced to the average reference. Finally, the data was split into one-second segments resulting in approximately 120 trials for each two-minute recording.

Time-frequency analysis

Similar to the preprocessing, the time-frequency analysis was done in Matlab using Fieldtrip (Oostenveld et al., 2011). The *ft_freqanalysis* function was used to perform time-frequency analysis on the preprocessed EEG data. We used a Hanning taper to transform the data into three frequency bands *theta* (4-9 Hz), *alpha* (9-14 Hz) and *beta* (14-28 Hz) (van Vugt, Simen, Nystrom, Holmes, & Cohen, 2012).

As was explained in the theoretical framework, the phase-locking value (PLV) and imaginary part of coherence can be used to determine whether there is inter-brain synchrony between two people. The phase-locking value was first introduced by Lachaux et al. (1999). Dumas et al. (2010); Hu et al. (2018); Mu et al. (2017), amongst others, used the work by Lachaux et al. (1999). The formula can be defined as:

$$PLV_{j,k,t} = \frac{1}{N}\left|\sum_{n=1}^{N} e^{i\phi_j(f,t)-\phi_{2k}(f,t)}\right| \tag{1}$$

With equation (1), the PLV is calculated as the absolute value of the sum of the phase differences between signals j and k ($\phi_j(f,t)-\phi_{2k}(f,t)$) across n[1 .... N] trials at time t and frequency f. In this formula, $i=\sqrt{-1}$. The PLV can take on values within the range of [0, 1]. If the PLV is close to 1, then this means that there is little phase difference between the two signals across the trials. If the PLV is close to 0, the opposite is the case. Thus, the closer the PLV is to 1, the more synchrony there is between the given electrodes of two people. To calculate the mean PLV we used the same formula as in equation (1). For the phase difference between the two signals, we extracted the angle from the cross-spectrum which was the result of the *ft_freqanalysis* function. As a final step, the average phase angle across all time was calculated. Since we are working with three frequency bands, the data was averaged across frequencies to get a mean phase-locking value (PLV) for each trial in each frequency band. This was done for each dyad, each condition and each similar electrode pair. We are only interested in determining the inter-brain synchrony measures for the same channel in each dyad. For example, we calculated the mean PLV for the Cz channel of participant one and participant two of one dyad.

In addition to the mean PLV, the imaginary part of coherence was also calculated. The calculation of the imaginary coherence was based on work from Nolte et al. (2004) and Dikker et al. (2021) and the function *ft_connectivity_corr* from Fieldtrip. The function from Fieldtrip that calculates imaginary coherence based on Nolte et al. (2004) averaged over the trial dimension, however, the trial dimension is of importance to see effects unfolding over time. Therefore, our implementation followed the work of Dikker et al. (2021) depicted in the following equation:

$$S_{jj}(f) = \sum_{t=1}^{N} X_j(t,f)\cdot X_j^*(t,f) \tag{2a}$$

$$S_{kk}(f) = \sum_{t=1}^{N} X_k(t,f)\cdot X_k^*(t,f) \tag{2b}$$

$$S_{jk}(f) = \sum_{t=1}^{N} X_k(t,f)\cdot X_j^*(t,f) \tag{2c}$$

$$C_{jk}(f) = \frac{S_{jk}(f)}{\sqrt{S_{kk}(f)S_{jj}(f)}} \tag{2d}$$

$$IC(f) = \left|imag(C_{jk}(f))\right| \tag{2e}$$

S_{jj} and S_{kk} are the auto-spectral densities of X_k (2a) and X_j (2b) respectively. X_j and X_k are the time series x_j and x_k that are transformed to the frequency domain of electrodes j and k. Next, the cross-spectrum, S_{jk}, between X_j and X_k is calculated using the complex conjugate (2c). Coherence is then calculated by normalizing the cross-spectrum (2d) resulting in C_{jk}. The phase of the complex number, C_{jk}, represents the average phase difference between x_j and x_k and the magnitude represents the consistency of the phase difference (Dikker et al., 2021). Finally, taking the absolute value of the imaginary part of coherence (2e). The imaginary part represents the lagged interactions and not the instantaneous interactions. Similar to the mean PLV calculation, the values for the imaginary coherence were averaged across all time followed by averaging across frequencies. This was, again, done for each dyad, each condition and each similar electrode pair.

Statistical Analysis

After running time-frequency analysis and calculating the mean phase-locking value (mean PLV) and imaginary coherence for the three frequency bands (*alpha*, *beta*, *theta*), we continued with the statistical analysis. The statistical analysis was conducted in R (R Core Team, 2020). We wanted to investigate the relationship between the inter-brain synchrony measures, the independent variable, and possible confounding variables.

Bauer, van Ede, Quinn, and Nobre (2021) showed the importance to consider cross-modal entrainment. In their study, they presented subjects with a continuous frequency-modulated sound and with a visual stimulus. They demonstrated that the sound affected the perception of the visual stimulus. Moreover, the sound also modulated the brain activity recorded in the visual electrodes. The frequency of the sound was found in the frequency representation of both the auditory and visual electrodes. The dyads in our study were engaged in movement on a metronome beat. The metronome beat was 80 bpm converting this to the frequency domain with the following calculation:

$$1 \text{ bpm} = \frac{1}{60} Hz$$

$$80 \text{ bpm} = \frac{80}{60} \approx 1,33 Hz$$

The lowest frequency of interest is 4 Hz belonging to the *theta* frequency band. Since $1,33Hz < 4Hz$, we conclude that the metronome beat will not be of influence on the statistical analysis.

Linear mixed-effects model. To investigate the relation between the conditions and the inter-brain synchrony measures linear mixed effect (LME) models were created using R's *lmerTest* package. One of the benefits of LME models is that it considers non-independence in the data. The non-independence that is present in the data is that it contains multiple observations from the same subjects. To compare the conditions in Table 1, we subsetted the data and created a model for each channel and frequency band separately. We were only interested in comparing the inter-brain synchrony measures between the two conditions for the same channel and not between other channel combinations or other conditions. Table 1 shows the five condition combination pairs, however, the **facing/not facing** and **synchronous/asynchronous** conditions consist of data points used in multiple conditions. As was explained in Section 3.1.3 the dyads moved in synchrony or asynchronous while either facing or not facing. Table 6 in appendix A shows an overview of how the data points were combined. For example, data from moving synchronously while facing was both used in the **facing** condition and in the **synchronous** condition. The same data point would be used in two conditions.

The models were simple, with the inter-brain synchrony measure as the dependent variable and the conditions as the independent variable with the dyads as a random intercept. However, most models resulted in an *isSingular* warning, meaning that the model was potentially overfitting the data. A possible explanation for this could be that there was insufficient data to build the models on. However, after taking a closer look, the individual intercepts that were created for each dyad were the same for most of the channels. For example, for the *AF3* channel comparing the **dialogue** with the **shift-of-focus** condition for the *theta* frequency band, the random intercept for the **dialogue** condition was 0.637. The random intercept for the **shift-of-focus** was 0.0021 lower. This was the same for all participants. Appendix B shows box plots of the imaginary coherence for the *AF3* channel in the *theta* frequency band for the **dialogue** condition in Figure 10a and the **shift-of-focus** condition in Figure 10b. The graphs support the results from the random intercepts that there are no large differences between the imaginary coherence values of dyads.

Generalized additive model. Instead of using overfitted LME models, we decided to use Analysis of variance (ANOVA) to investigate the relation between the inter-brain synchrony measures and the conditions. However, unlike for LME the imaginary coherence values and mean PLV needed to be averaged over trials. More about ANOVAs in the next paragraph. By averaging over the trials effects that unfold over time are lost. In addition to ANOVA, we also used Generalized additive models (GAM) (Hastie & Tibshirani, 1990) to see the effects unfolding over time. A benefit of GAM is that the relation between the dependent and independent variables can either be linear or nonlinear without declaring this in advance. This allows us to model dependence on time, which may not be linear. To create the models, we used the *gam()* function from R's *mgcv* package, and for visualization, we used the *itsadug* package.

The visualizations of the GAM models showed that the significant difference between the two conditions, for some channels, was only in the final trials. Moreover, for some channels, the difference between the two conditions was significant for the majority of trials but not in the final trials. Taking a closer look at the data, we found that not for all channels there was data from each dyad for 120 trials but only up till trial 90. So, instead of using data from 120 trials, data up until trial 90 was used for further analysis.

The *gam* models gave the warning that the random effect for dyads was cancelled. This is in line with the findings from the linear mixed-effects models. We argued that this might be caused by the differences between dyads being too small. In addition, the models were created using the trial variable to investigate the effects over time. The trials for the dyads were not comparable since there was no choreography to which they needed to adhere to. The dyads could move freely to their interpretation of the conditions. Even though the results from the *gam* model could show the effects of moving in various conditions on inter-brain synchrony over time, for the scope of this study, we were more interested in the effect of the conditions on inter-brain synchrony. The *gam* models helped us discover that there were not 120 trials of data for each dyad. Nonetheless, the results from the *gam* models will not be considered for further interpretation due to the reasons mentioned in this paragraph.

Analysis of variance. To investigate the relationship between the inter-brain synchrony measures and various independent variables we decided to use ANOVA. The ANOVA models were created using the *aov()* function from R's *stats* package. Furthermore, these models contained an error for dyads over the conditions. We created separate models for the conditions pairs since we are only interested in comparing the conditions depicted in Table 1. Besides creating different models for the conditions, a separate model was created for each channel and each frequency band.

First, we wanted to inspect the relation between the conditions and the inter-brain synchrony measures using a one-way repeated measure ANOVA with the condition pairs as the independent variable. Since the dyads performed all conditions, we are dealing with repeated measures.

Next, we wanted to investigate the possible effect of various aspects of the dyads on the inter-brain synchrony measures. Cheng, Li, and Hu (2015) found gender differences in interpersonal neural synchronization during cooperation. 32% of the dyads that participated in the experiment had the same gender. Besides recording the gender of the dyads, the relation and frequency of contact of the dyads were also recorded. Dikker et al. (2021) found that the pairs that knew each other well showed more inter-brain synchrony compared to pairs who did not know each other. Additionally, Kinreich, Djalovski, Kraus, and Louzoun (2017) found that there was neural synchronization for couples during social interaction but not for strangers. In addition to looking at the effect of condition on the inter-brain synchrony measures, the effect of gender, the closeness of relation and frequency of contact on the inter-brain synchrony measures were also investigated. Two-way mixed ANOVA models were created for *same gender dyads*, *frequency of contact*, and *closeness of relation* while controlling for the effect of the condition. The frequency of contact and the closeness of relation varied over dyads. Hence the dyads were divided into two groups, the *frequent* and *not frequent* contact and *close* and *not close* relationship. Appendix C shows the division of various frequencies of contact per group in Table 7 and the varying relationships per group in Table 8. 52% of the dyads belonged to the *frequent* contact group, and 44% of the dyads belonged to the *close* relation group.

Each participant provided a rating [0, 10] on how mentally and physically connected they felt to the other participant for every condition. We conducted a paired t-test to determine whether the difference between the social and nonsocial condition pairs was statistically significant. After this, we continued investigating the relationship between the inter-brain synchrony measures and the subjective ratings. In order to do this, the subjective ratings from both participants in a dyad were combined. First, the average rating between the two participants from a dyad was calculated. Besides calculating the average rating, the difference between the ratings within a dyad was calculated, since calculating an average does not take into account (large) variances within a dyad. These two measures were combined to divide the dyads into one of three possible groups, '*high difference*', '*low difference and low average*', or '*low difference and high average*'. To try and achieve three balanced groups for both mental and physical connection, the dyads were divided into groups irrespective of condition. However, the groups were still unbalanced. Appendix D shows the division of dyads of the subjective ratings for mental connection in Table 9 and physical connection in Table 10. These rating groups were used in a two-way mixed ANOVA to investigate the relation between the inter-brain synchrony measures and the subjective ratings while controlling for the condition.

For this analysis, the multiple comparisons problem was present, since the data for 32 channels were compared between and within-subjects. Consequently, all the p-values were adjusted with the *p.adjust* function from R's *stats* package. Pérez, Carreiras, and Duñabeitia (2017) computed inter-brain synchrony using the phase-locking value and they used the Benjamini and Hochberg correction for multiple comparisons. A benefit of using the FDR method to adjust the p-values is that besides minimizing false negatives it also reduces false positives (Jafari & Ansari-Pour, 2019). Therefore, the Benjamini and Hochberg method, also known as the FDR method, was used for adjusting the p-values.

Table 2: Overview of the various conducted analyses with the corresponding research questions. Analyses for the inter-brain synchrony (IBS) measures, imaginary coherence and mean PLV, were done separately. Moreover, the analyses were also done separately for each frequency band.

Analysis	**Research Question**
Paired t-test for subjective ratings (mental) between social and nonsocial condition pairs	Do dyads subjectively experience to feel more mentally connected while moving in the social conditions compared to the nonsocial conditions?
Paired t-test for subjective ratings (physical) between social and nonsocial condition pairs	Do dyads subjectively experience to feel more physically connected while moving in the social conditions compared to the nonsocial conditions?
One-way repeated measures ANOVA assessing effects of conditions on IBS	Does moving in various social and nonsocial conditions induce IBS?
Two-way mixed ANOVA assessing effects of condition x Subjective rating (mental) on IBS	Is feeling more mentally connected to a partner associated with IBS while controlling for condition?
Two-way mixed ANOVA assessing effects of condition x Subjective rating (physical) on IBS	Is feeling more physically connected to a partner associated with IBS while controlling for condition?
Two-way mixed ANOVA assessing effects of condition x Gender on IBS	Does the gender of the dyads affect the degree of IBS while controlling for conditions?
Two-way mixed ANOVA assessing effects of condition x Relationship on IBS	Does the relationship of the dyads affect the degree of IBS while controlling for conditions?
Two-way mixed ANOVA assessing effects of condition x Frequency of contact on IBS	Does the frequency of contact of the dyads affect the degree of IBS while controlling for conditions?

3.2 Moving in the wild

3.2.1 Participants

Two professional dancers from the dance company Random Collision were the volunteers participating in the experiment. Both the dancers were males. Besides being professional dancers, they were also experts in exploring social connection through movement. They had been previously involved in research investigating social connection with van Mourik Broekman, Gordijn, Postmes, Koudenburg, and Krans (2015).

3.2.2 Equipment and procedure

The same equipment and placement of electrodes were used for hyperscanning the professional dancers as in the laboratory experiment. As mentioned in section 3.1.5 the conditions from the laboratory experiment were based on the conditions from this performance. The conditions were not the same as the conditions for the professional dancers. The performance needed to have sufficient theatrical quality to work as output of movement choreographers. The performance could be divided into five conditions; **void to identification**, **tendus to mechanical**, **one-body**, **dialogue** and **shift-of-focus**. The last three conditions are similar to the conditions described in section 3.1.3. In the **void to identification** condition, the dancers tried to connect on a metaphysical level by travelling back to the sense of self. In the **tendus to mechanical** condition the dancers tried to connect on a logical structure, this was done by synchronizing on a beat. The **shift-of-focus** condition was only entered after the **dialogue** condition was successful. The conditions were performed in the same order at the different festival locations. Unlike the dyads in the laboratory experiment, the dancers could move freely without confining movements to the arms and hands. The dancers were not dancing to a metronome beat but to various pieces of live composed music, for each condition a different piece was composed.

The dance performance was done in six different cities in the Netherlands as part of the Moving Futures festival 2019. The data from the cities Utrecht, Tilburg and Amsterdam were used for the analysis. The data from the other three cities was discarded because it was too noisy or due to technical difficulties, for example, for one city the data of only one dancer was recorded. For Utrecht and Tilburg there was only data from the **Void to identification** and **Tendus to Mechanical** condition. These two conditions were the first two conditions, after that the electrodes got loose due to intense movement.

3.2.3 Data processing and analysis

For the EEG data of the professional dancers, the EEG preprocessing and the time-frequency analysis were the same, as described in 3.1.5. Also, the mean PLV was calculated the same way as is described in section 3.1.5. The imaginary coherence was, however, calculated differently. The imaginary coherence from the laboratory experiment was higher on average than expected. Even though the height of the imaginary coherence was consistent, we decided to use Fisher's z transformation on the imaginary coherence before averaging across time and frequencies. Englot et al. (2015); Hinkley et al. (2011); Rolston and Chang (2017) all used imaginary coherence to determine functional connectivity and they all transformed the imaginary coherence with Fisher's z transformation before averaging or taking the median. Furthermore, unlike the laboratory experiment where the mean PLV and imaginary coherence was calculated for each channel pair, the inter-brain synchrony measures were calculated only for those channel pairs that were statistically significant in the laboratory experiment. Since we only gathered data from two professional dancers, the results cannot be generalized over a population, hence we did not perform statistical analysis on this data. Therefore, we decided to visually inspect the data and see whether similar trends would be visible in the data from the dancers. Besides visually inspecting the data for inter-brain synchrony trends, this opportunity allows us to compare the two inter-brain synchrony measures. More importantly, besides comparing the mean PLV and the transformed imaginary coherence, we will also compare these measures to the imaginary coherence computed without Fisher's z transformation.

Unlike the exact timing for the conditions of the laboratory experiment, the conditions from the professional dancers were less exact. The inter-brain synchrony was calculated for each one-second trial. However, the conditions were of various lengths and the EEG recorded data as well. Moreover, the same condition in different cities varied in length. For visualization, the inter-brain synchrony measures were binned to 30 seconds or 60 seconds for the **void to identification** condition. An average inter-brain synchrony value was then calculated for each bin. There was one recording for the **dialogue** and **shift-of-focus** conditions. To split the data into the corresponding conditions, the timings were extracted by watching the recordings of the performances. Hence, the ending of the **dialogue** and the beginning of the **shift-of-focus** condition might not be completely correct. Moreover, watching the dancers perform in the **shift-of-focus** condition at a certain point the dancers are sitting on the floor face-to-face. This behaviour is opposite to the essence of the **shift-of-focus** condition. We are uncertain whether this is part of the EEG recordings or whether the recording of brain activity was already stopped. Thus, the ending of the **shift-of-focus** condition might not be the **shift-of-focus** condition. The uncertainty about the start and the end of the conditions and how exactly they coincide with the EEG recordings applies to all the conditions and cities. For example, after the conditions, there was a moment of transition before the next condition. It was unclear when one EEG recording stopped and when the next one started.

4 Results

4.1 Laboratory experiment

4.1.1 Subjective Ratings

We wanted to investigate whether moving in various social and nonsocial conditions could induce inter-brain synchrony. To answer this question, participants were asked to move in various conditions and provide subjective ratings for each condition. Before presenting the results from the inter-brain synchrony, we first present the results from the subjective ratings. The dyads provided a rating for both mental and physical connection separately. The social conditions were designed to socially connect the dyads and hopefully induce inter-brain synchrony compared to the nonsocial conditions. First, we wanted to know whether the conditions made the dyads feel connected to one another. As was explained in paragraph 3.1.5 there is an average rating for each dyad, for each condition and for both physical and mental connectedness. Figure 1 shows the average rating for each condition for both mental and physical connectedness. The graph shows that the average rating for mental connection was highest for the **dialogue** condition and the average rating for physical connection was highest for the **one-body** condition. Except in this latter condition, the average rating for the physical connection is lower compared to the mental connection. The average rating for mental and physical connection is lowest for the **alone** condition.

The results from the paired t-test showed that the subjective ratings are significantly higher in; the **facing** condition compared to the **not facing** condition, the **dialogue** condition compared to the **shift-of-focus** condition, the **one-body** condition compared to the **shift-of-focus** condition and the **one-body** condition compared to the **alone** condition for both mental and physical connectedness ($9 < t < -16$, $p < .001$). The individual results from the paired t-test are presented in Table 3 for both mental and physical connectedness. Dyads report to feel more mentally and physically connected in the social conditions, **facing, dialogue, one-body**, compared to the nonsocial conditions, **not facing, shift-of-focus, alone**, except when comparing **synchronous** vs. **asynchronous**. The **facing** and **synchronous** condition pairs consisted of combined data points. For example, the **facing** condition consists of subjective ratings from moving synchronously and asynchronously while the dyads were facing each other. Figure 11 in Appendix E shows the average rating for the facing and synchronous conditions separately. Whether the dyads are facing each other appears to have more influence on the subjective experience of connection compared to moving either synchronously or asynchronously. In conclusion, dyads significantly report to feel more physically and mentally connected while moving in the social conditions compared to moving in their nonsocial counter condition except for the **synchronous** condition.

Table 3: Results from the paired t-test of the subjective ratings for mental and physical connectedness. The degrees of freedom for the first two condition pairs are higher compared to the other three condition pairs because the **facing** and **synchronous** condition pairs are combined measurements (See methods).

Condition	Mental connectedness	Physical connectedness
Facing vs. Not facing	t(49) = 16.03***	t(49) = 9.91***
Synchronous vs. Asynchronous	t(49) = 1.1	t(49) = 1.31
Dialogue vs. Shift-of-Focus	t(24) = 11.2***	t(24) = 10.16***
One-Body vs. Shift-of-Focus	t(24) = 9.49***	t(24) = 13.57***
One-Body vs. Alone	t(24) = -16.04***	t(24) = -19.7***

* p <.05; ** p < .01; *** p < .001

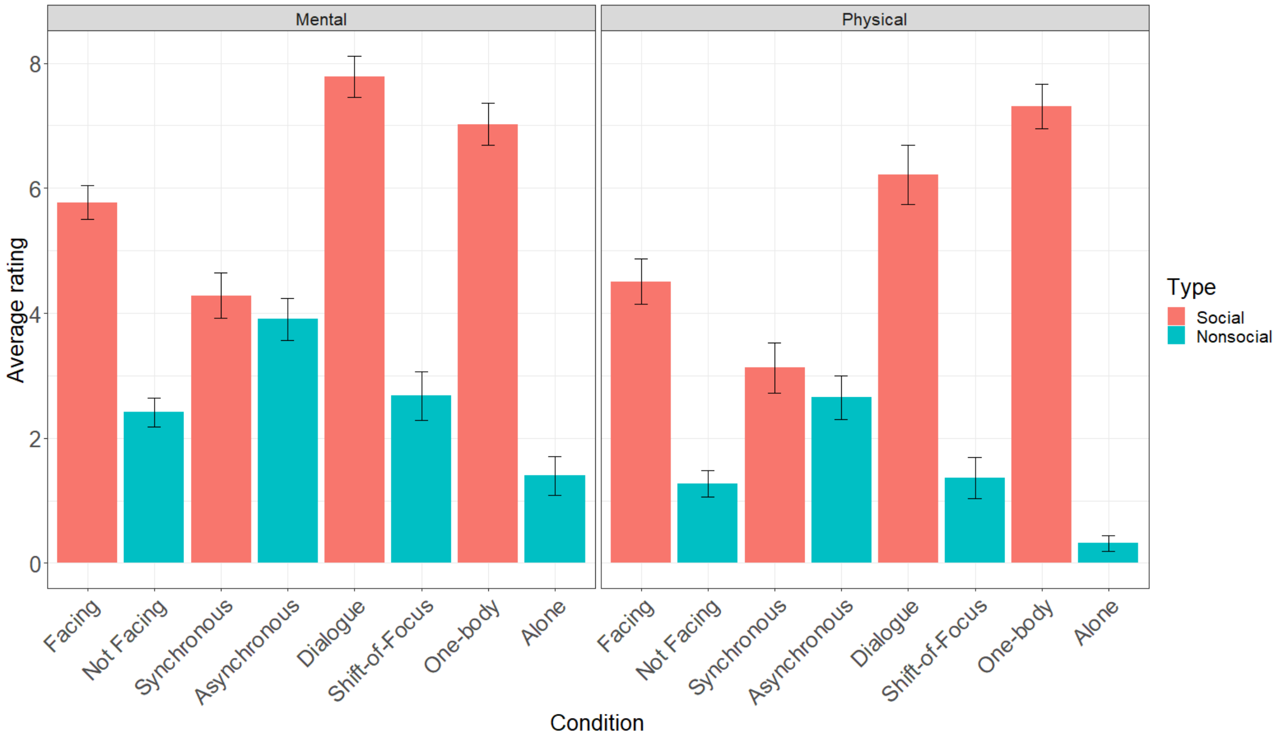
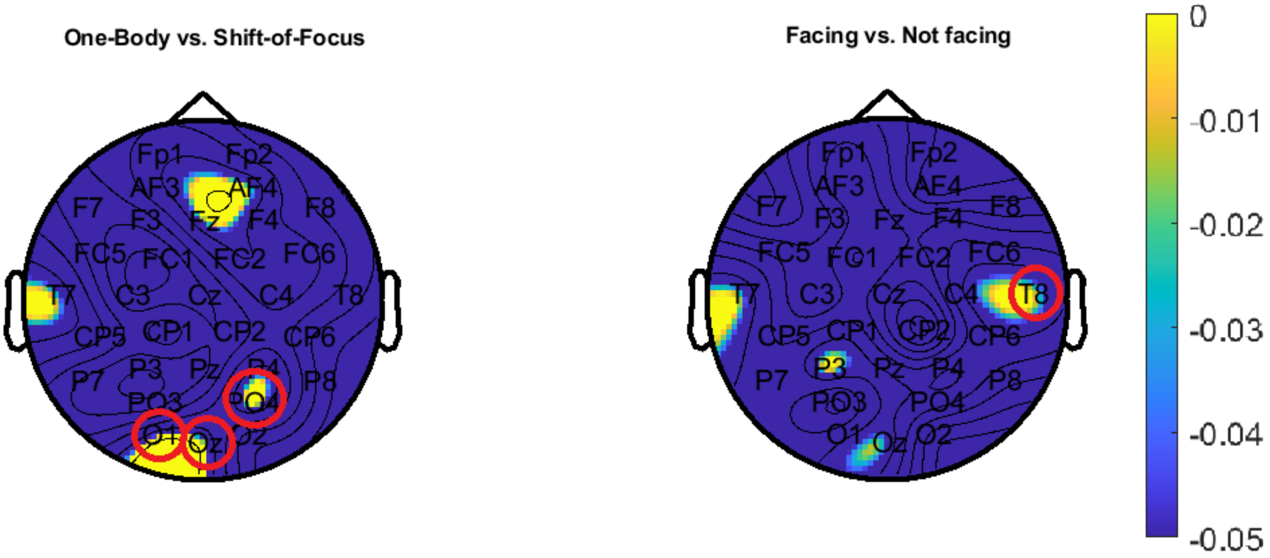


Figure 1: Average subjective ratings, both mental and physical connection, for each condition with standard error bars.

4.1.2 Inter-brain synchrony

Inter-brain synchrony refers to the neural couplings between people. To estimate the inter-brain synchrony within dyads under various conditions we calculated the mean phase-locking value (PLV) and imaginary coherence (see Methods). First, the results from the one-way ANOVA for assessing the effects of the social and nonsocial conditions on inter-brain synchrony will be discussed. Next, the results from the two-way repeated-measures ANOVA for assessing the effects between the subjective experience of the dyads and inter-brain synchrony will be discussed. Finally, we will present the



(a) *Theta* band 4-9 Hz

(b) *Alpha* band 9-14 Hz.

Figure 2: (a) The effect of moving as one-body vs. shift-of-focus. (b) The effect of moving while facing each other and not facing. Yellow indicates a significant difference in inter-brain synchrony, **mean phase-locking value**, between the two conditions whereas blue indicates no significant difference. The red circled channels survived the p-value correction.

results from the modulating factors on the inter-brain synchrony measures.

Inter-brain synchrony during movement

In this section, results for answering whether moving in various social and nonsocial conditions induces inter-brain synchrony will be presented.

Theta frequency band [4-9 Hz]. The results of the one-way ANOVA showed that for the conditions **one-body** vs. **shift-of-focus** the channels *O1* (F(1, 24) = 16.4, FDR-corrected $p < 0.05$), *PO4* (F(1, 24) = 14.17, FDR-corrected $p < 0.05$), and *Oz* (F(1, 24) = 11.57, FDR-corrected $p < 0.05$) had a significant difference in the mean PLV. Figure 2a illustrates a topographical plot of the significant channels. Table 4 shows the mean PLV on average for the three channels and the corresponding condition. The mean PLV is significantly higher in the **one-body condition** condition for the three channels compared to the **shift-of-focus**.

Table 4: The mean phase-locking values for the three significant channels surviving the p-value correction for the *theta* band with standard error.

Channel	One-body	Shift-of-focus
O1	0.434 (SE = 0.01)	0.424 (SE = 0.01)
PO4	0.435 (SE = 0.011)	0.425 (SE = 0.011)
Oz	0.432 (SE = 0.011)	0.423 (SE = 0.011)

Alpha frequency band [9-14 Hz]. The results of the one-way ANOVA illustrated that there was a significant difference between the mean PLV from the **facing** vs. **not facing** conditions in the *T8* channel (F(1, 49)=13.15, FDR-corrected $p < 0.05$). Figure 2b shows that the *T7* channel also was significant before the p-value correction, however, it was not significant anymore after the p-value correction. Thus, these results indicate that there is less inter-brain synchrony in the temporal area for the **facing** condition compared to the **not facing** condition (Table 5b).

Besides the significant result for the mean PLV, there was also a significant result for the imaginary coherence. Namely, the imaginary coherence was significantly lower in the **one-body** condition compared to the **shift-of-focus** condition for the *O1* channel (F(1, 24) = 14.17, FDR-corrected $p < 0.001$). The result is visualised in Figure 3 and this shows that besides the *O1* channel also the *FC1*, *CP5* and *T7* channels were significant before the p-value correction. The result that survived the p-value correction implies that there is less inter-brain synchrony in the parietal-occipital area in the **one-body** condition in comparison to the **shift-of-focus** condition (Table 5a). Figure 3 also presents a topographic map of the head for the **synchronous** vs. **asynchronous** conditions. Here we see that that the imaginary coherence was higher in the **synchronous** condition compared to the **asynchronous** condition for the *CP1* channel (F(1, 49) = 13.23, FDR-corrected $p < 0.05$). The topographic map also shows that the *FC5* channel was significant before the p-value correction but not after. Table 5a shows that there is more inter-brain synchrony in the central parietal area in the **synchronous** condition compared to the **asynchronous** condition.

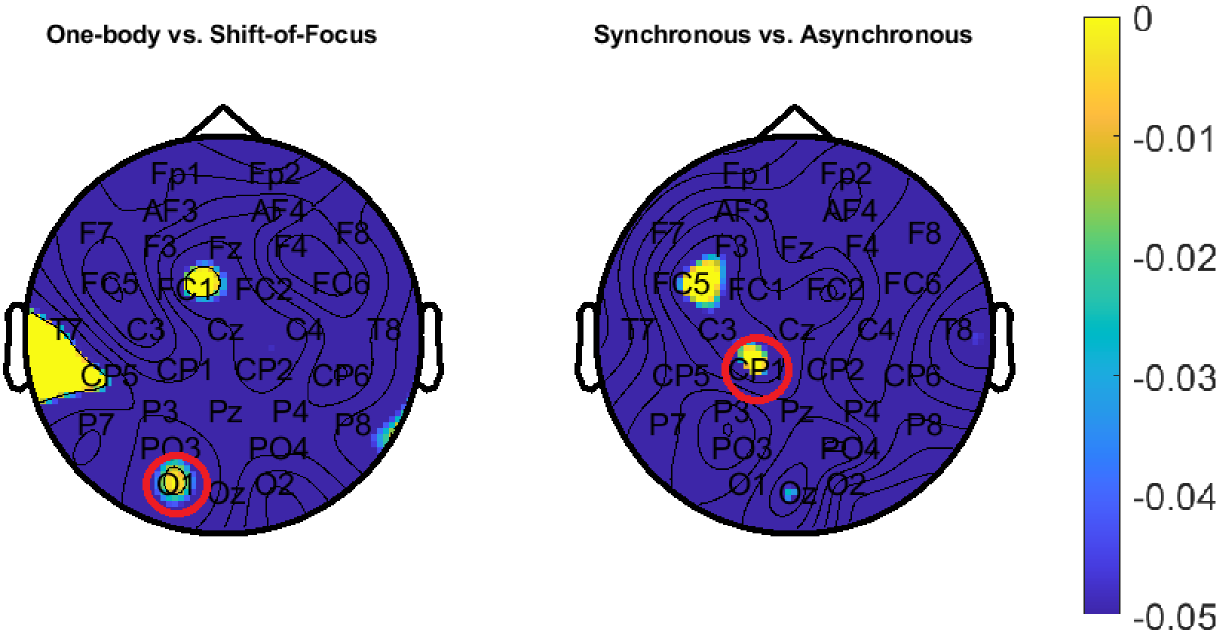


Figure 3: The effect of moving as one-body vs. shift-of-focus and moving synchronous vs asynchronous in the *Alpha* band 9-14 Hz. Yellow indicates a significant difference in inter-brain synchrony, **imaginary coherence**, between the two conditions whereas blue indicates no significant difference. The circled channels survived the p-value correction.

Beta frequency band [14-28 Hz]. The results of the one-way ANOVA to investigate the effect of the conditions on the inter-brain synchrony in the *beta* band did not survive the p-value correction for the multiple comparison problem for either the mean PLV or the imaginary coherence. Therefore, the

Table 5: The average inter-brain synchrony values for the three significant channels surviving the p-value correction for the *alpha* band with standard error.

(a) **Imaginary coherence**

Channel	Condition	IC
O1	One-body	0.63 (SE = 0.001)
	Shift-of-focus	0.64 (SE = 0.001)
CP1	Synchronous	0.64 (SE = 0.001)
	Asynchronous	0.63 (SE = 0.001)

(b) **Mean phase-locking value**

Channel	Condition	mean PLV
T8	Facing	0.32 (SE = 0.002)
	Not facing	0.33 (SE = 0.001)

two-way mixed ANOVAs were not executed for the *beta* band.

So, for the *theta* band, there is more inter-brain synchrony in the parietal-occipital area for the **one-body** condition compared to the **shift-of-focus** condition. This was only for the mean PLV and not for the imaginary coherence. In the *alpha* band, on the other hand, there are significant results for both inter-brain synchrony measures. There is a significant difference in inter-brain synchrony between varying social and nonsocial conditions and for various brain areas. These results suggest that moving in various conditions affects inter-brain synchrony in the *alpha* and *theta* band but not in the *beta* band.

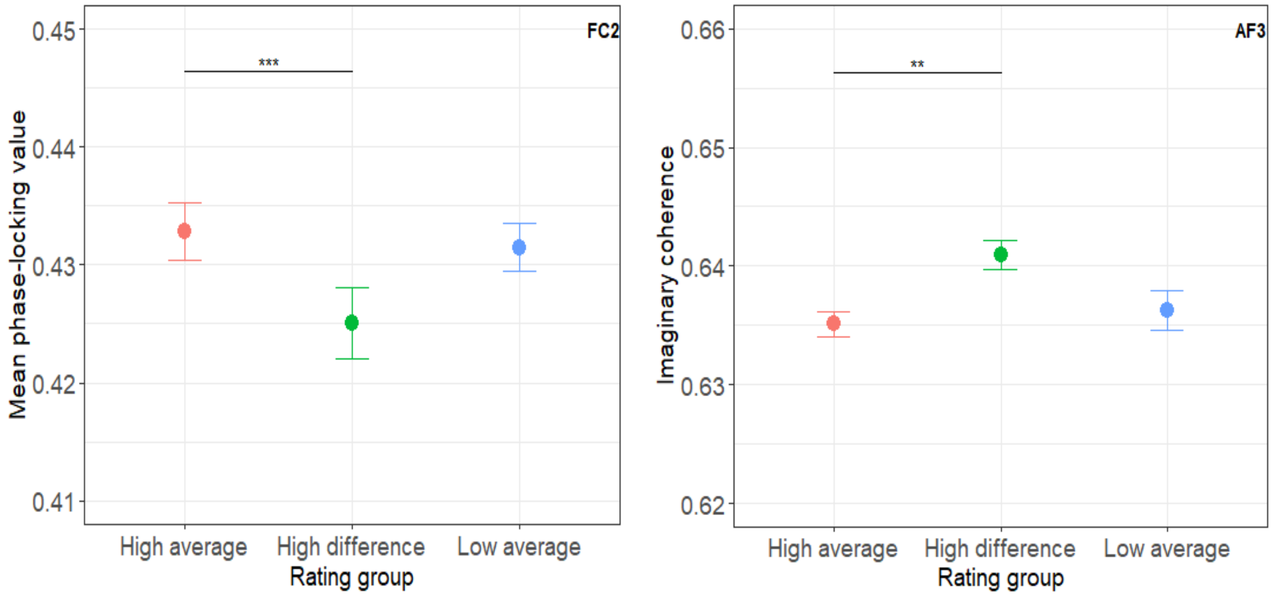
We also looked at whether the mean PLV and the imaginary coherence were correlated. The results are presented in Table 11 in Appendix F. The results showed that the two measures were not correlated (all $-0.4 < r_{rm} < -0.002$, $p > 0.05$).

The subjective experience and Inter-brain synchrony

In this section, the results for answering the following question are presented; ”Is feeling more mentally or physically connected to a partner associated with inter-brain synchrony while controlling for the conditions?”

Theta frequency band [4-9 Hz]. The one-way ANOVA was followed by a two-way repeated-measures ANOVA for investigating the relationship between the subjective ratings and the inter-brain synchrony while controlling for the conditions. For the *theta* band, there was not a significant interaction between the conditions and the subjective rating groups. There was, however, a significant main effect of the mental rating group on the mean PLV of the *FC2* channel in the **one-body** vs. **shift-of-focus** condition (F(2, 24) = 9.99, FDR-corrected $p < 0.05$). Post-hoc analysis revealed that the inter-brain synchrony is higher for the *high average* subjective rating group compared to the *high difference* subjective rating group (t(21)=4.36, FDR-corrected $p < 0.001$). The results are visualised in Figure 4a. Thus, these results suggest that when dyads report feeling more mentally connected, irrespective of the condition, there is more inter-brain synchrony in the frontal-central area compared to dyads that have a discrepancy in how connected they feel.

Alpha frequency band [9-14 Hz]. Similar to the the two-way ANOVA for the *theta* band, there was not a significant interaction between the conditions and the mental and physical subjective rating groups. There was, however, a significant main effect of the mental rating group on the imaginary coherence of the *AF3* channel in the **one-body** vs. **shift-of-focus** condition (F(2, 21) = 12.18, FDR-



(a) *Theta* band 4-9 Hz (**FC2**) (b) *Alpha* band 9-14 Hz (**AF3**)

Figure 4: The difference in inter-brain synchrony for the mental connectedness subjective rating groups. (a) The significant difference in the **mean phase-locking values** between the *high average* and *high difference* rating groups in the *FC2* channel. (b) The significant difference in the **imaginary coherence** between the *high average* and *high difference* rating groups in the *AF3* channel with standard error bars.
* $p < .05$; ** $p < .01$; *** $p < .001$

corrected $p < 0.05$). Post-hoc analysis showed that the inter-brain synchrony is higher for the *high difference* subjective rating group compared to the *high average* rating group (t(21) = -3.63, FDR-corrected $p < 0.01$). The results are visualised in Figure 4b. So, these results suggest that there is more inter-brain synchrony in the anterior-frontal area in the *alpha* band in dyads that have a discrepancy in how mentally connected they feel, again irrespective of condition, compared to dyads whom subjectively experience more mental connectedness.

Neither for mental connect nor for physical connection was their a significant interaction between condition and the subjective rating group on inter-brain synchrony. However, there appears to be a relationship between feeling mentally connected and inter-brain synchrony. Notably, irrespective of condition, the significant results from both the mean PLV and imaginary coherence are in comparing the **one-body** and **shift-of-focus** conditions. Another noteworthy result is that the effects of the mental rating group are opposite for the two inter-brain synchrony measures. Where there is more inter-brain synchrony for the *high average* rating group in the mean PLV for the *theta* band, there is more inter-brain synchrony for the *high difference* rating group in the imaginary coherence for the *alpha* band.

Modulating factors on Inter-brain synchrony

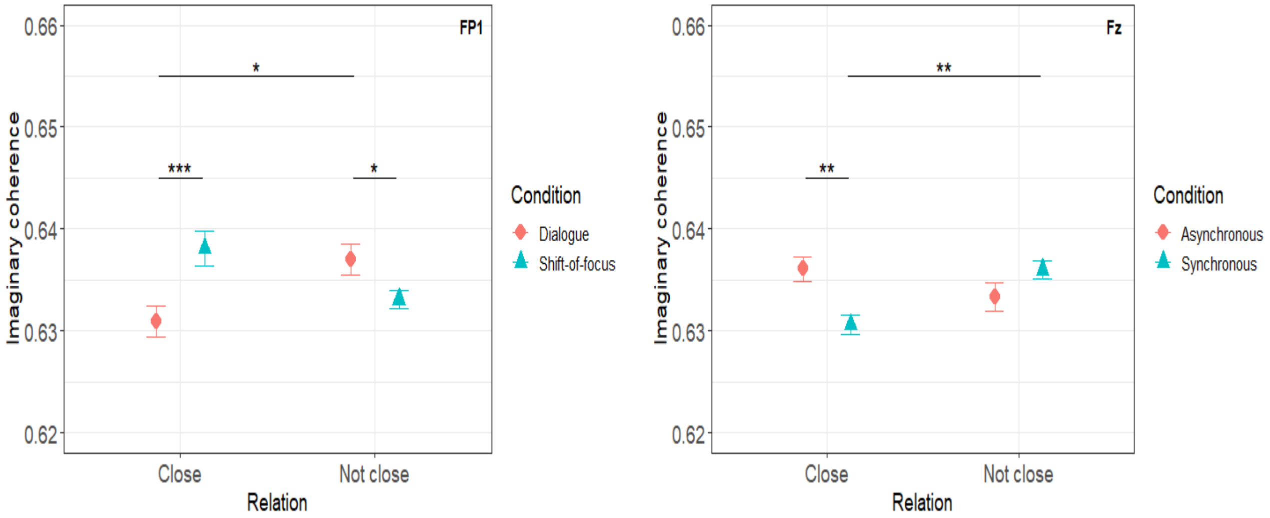
In this final section, the results for answering whether there are modulating factors affecting the degree of inter-brain synchrony while controlling for conditions will be presented. The factors include the gender, the relationship and the frequency of contact of the dyads.

Theta frequency band [4-9 Hz]. Lastly, we ran a two-way mixed ANOVA for investigating the relationship between the inter-brain synchrony measures and the gender of the dyads, frequency of contact of the dyads and the relationship between the dyads. There was a significant interaction between the relationship of the dyads and the **dialogue** vs. **shift-of-focus** condition in the *FP1* channel on the imaginary coherence (F(1,23) = 28.12, FDR-corrected $p < 0.01$). Post-hoc analysis revealed that dyads that have a close relationship showed less inter-brain synchrony in the **dialogue** condition compared to the **shift-of-focus** condition (t(23) = -4.59, FDR-corrected $p < 0.001$). In addition, for the **dialogue** condition, there appears to be less inter-brain synchrony for the dyads that have a close relationship compared to the dyads that do not have a close relationship (t(23) = -3.04, FDR-corrected $p < 0.05$). There also seems to be more inter-brain synchrony in the **dialogue** condition compared to the **shift-of-focus** when the dyads do not have a close relationship (t(23) = 2.81, FDR-corrected $p < 0.05$). These results are visualised in Figure 5a and suggest that the closeness of the relation of the dyads is of influence on inter-brain synchrony in the anterior-frontal area in comparing moving in a **dialogue** vs. moving with a **shift-of-focus**.

Furthermore, there was also a significant interaction for the **synchronous** vs. **asynchronous** condition and the relationship of the dyads on the imaginary coherence for the *Fz* channel (F(1, 23) = 22.89, FDR-corrected $p < 0.01$). Post-hoc analysis revealed that dyads that have a close relationship show less inter-brain synchrony in the **synchronous** condition compared to the **asynchronous** condition (t(23) = 4.29, FDR-corrected $p < 0.01$). Additionally, when moving **synchronously** there is more inter-brain synchrony in dyads that are not close compared to dyads that are close (t(23) = -3.68, FDR-corrected $p < 0.01$). The results are visualised in Figure 5b and suggest that the closeness of the relation of the dyads affects the inter-brain synchrony measure, imaginary coherence, in the frontal area when comparing moving synchronously to moving asynchronously.

Alpha frequency band [9-14 Hz]. The two-way mixed ANOVA investigating various aspects of the dyads and the conditions showed that there is a significant interaction between the gender of the dyads and the **one-body** vs. **shift-of-focus** condition in the *PO4* channel on the imaginary coherence (F(1,23) = 15.14, FDR-corrected $p < 0.05$). Post-hoc analysis revealed that the imaginary coherence for dyads with different genders tends to be higher in the **one-body** condition compared to dyads that have the same sender and move in the **shift-of-focus** condition (t(23) = 2.85, FDR-corrected $p < 0.05$). This finding contains both conditions and both gender groups and will therefore not be considered for further discussion. In addition, when moving in the **shift-of-focus** condition the imaginary coherence is higher for dyads that have different genders compared to dyads with the same gender (t(23) = 3.71, FDR-corrected $p < 0.01$). Moreover, for dyads with the same gender the imaginary coherence is higher in the **one-body** condition compared to the **shift-of-focus** condition (t(23) = 3.91, FDR-corrected $p < 0.01$). The results are visualised in Figure 6a. The results suggest that there is more inter-brain synchrony in the parietal-occipital area when dyads of the same gender move in a social condition, **one-body**, compared to moving in a nonsocial condition, **shift-of-focus**. Besides, the results imply that dyads that do not have the same gender have more inter-brain synchrony in the parietal-occipital area when moving in a nonsocial condition, **shift-of-focus**, compared to dyads with the same gender.

For the *alpha* band we found the relationship of the dyads to affect inter-brain synchrony for the **facing** vs. **not facing** condition. The result was for the mean PLV in the *C4* channel (F(1,23) = 22.47, FDR-corrected $p < 0.05$). Post-hoc analysis showed that the mean PLV is higher in the **not facing** condition when the dyads do not have a close relationship compared to dyads that are close (t(23) = -3.1, FDR-corrected $p < 0.05$). Finally, when the dyads do not have a close relationship the mean PLV is lower in the **facing** condition compared to the **not facing** condition (t(23) = 4.6,



(a) *Theta* band 4-9 Hz (**FP1**)

(b) *Theta* band 4-9 Hz (**Fz**)

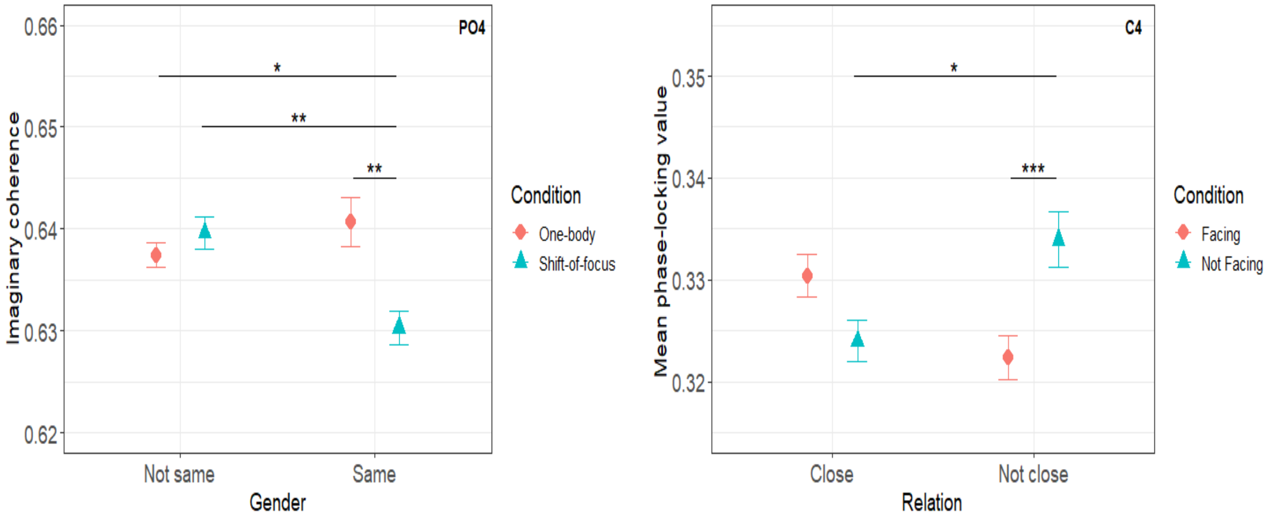
Figure 5: The difference in **imaginary coherence** in dyads with varying closeness of relation (a) for the **dialogue** vs. **shift-of-focus** condition in the *FP1* channel and (b) for the **synchronous** vs. **asynchronous** condition in the *Fz* channel with standard error bars.
* p <.05; ** p < .01; *** p < .001

FDR-corrected p < 0.001). The results are visualised in Figure 6b. The results suggest that there is more inter-brain synchrony in the central area in a nonsocial condition, **not facing**, when the dyads are not close compared to dyads that are close. Moreover, the results also indicate that there is more inter-brain synchrony in the central area for dyads that are not close when they move in a nonsocial condition, **not facing**, compared to moving in a social condition, **facing**.

So, there are modulating factors that affect the inter-brain synchrony when moving in social and nonsocial conditions. In the *theta* band, the closeness of the relationship of the dyads affected the imaginary coherence in the (anterior) frontal area in the **dialogue** vs **shift-of-focus** and **synchronous** vs **asynchronous** conditions. Besides the relationship, also the gender of the dyads affected the imaginary coherence in parietal-occipital area in the **one-body** vs. **shift-of-focus** conditions in the *alpha* band. Additionally in the *alpha* band, the closeness of relation affected the mean PLV in the central area in the **facing** vs. **not facing** conditions.

4.2 Moving in the wild

The channels that were found to be significant in the laboratory experiment were used to narrow down the number of channels for analysing the data from the professional dancers. However, as was described in the Method section, the conditions between the laboratory experiment and the conditions from the Moving Futures festival did not fully overlap. The conditions that did overlap were the **one-body**, **shift-of-focus** and the **dialogue** condition. Based on the results of the ANOVAs we decided to look at the following channels *O1*, *PO4* and *Oz* for both the *theta* and *alpha* frequency band. The results of the one-way repeated-measures ANOVA showed that the mean PLV was significantly higher in the **one-body** condition compared to the *shift-of-focus* condition in the *theta* band for these three channels (Table 4). In addition, the imaginary coherence was significantly lower in the **one-body** condition compared to the **shift-of-focus** condition in the *alpha* band (Table 5a). Besides the results



(a) Imaginary coherence (**PO4**) (b) Mean phase-locking value (**C4**)

Figure 6: Inter-brain synchrony in the *Alpha* band 9-14 Hz. (a) The effect of gender on the imaginary coherence for the **one-body** vs. **shift-of-focus** condition in the *PO4* channel. (b) The effect of the closeness of the relationships between dyads on the **mean phase-locking value** for the **facing** vs. **not facing** condition in the *C4* channel. Both with standard error bars.
* $p < .05$; ** $p < .01$; *** $p < .001$

of the one-way ANOVA, also the results of the two-way mixed ANOVA showed the importance of the *PO4* channel. Namely, the imaginary coherence was significantly higher for the **one-body** condition compared to the **shift-of-focus** when the dyads had the same gender in the *alpha* band (See Figure 6a). The dancers are both male and thus of the same gender.

The results from the two-way mixed ANOVA further demonstrated that the imaginary coherence was significantly lower in the **dialogue** condition compared to the **shift-of-focus** condition in the *FP1* channel for dyads that had a close relationship (See Figure 5a). The two professional dancers are both part of the same dance company, thus they work and dance with each other regularly. The relationship between the two dancers can be described as close rather than not close. For this reason, channel *FP1* for the **dialogue** and **shift-of-focus** conditions for the *theta* frequency band was chosen.

In the **tendus to mechanical** condition, the dancers synchronised to a beat. **Synchronous** movement was one of the conditions for the dyads in the laboratory experiment. For the **tendus to mechanical** condition we will, thus, look at the channels *CP1* and *Fz* who were found to be significant in comparing the **synchronous** vs. **asynchronous** conditions. The imaginary coherence in the *CP1* channel was significantly higher for the **synchronous** condition in comparison to the imaginary coherence in the **asynchronous** condition for the *alpha* band (Table 5a). The opposite was true for the *Fz* channel, in the *theta* band, where the imaginary coherence was significantly higher for the **asynchronous** condition compared to the **synchronous** condition when the dyads had a close relationship (See Figure 5b). As was stated above, we infer that the two dancers have a close relationship. It has to be noted that the results from the laboratory experiment were based on comparing two conditions. This is not possible for **tendus to mechanical** and the **void to identification** conditions. The latter condition is most similar to the **alone** and **not facing** conditions in the laboratory experiment because the dancers were more focused on themselves compared to the other dancer. There were no significant results in comparing the **alone** condition, there was, however, a significant result when comparing the **facing** vs. **not facing** condition. In the *T8* channel, the mean PLV was higher in the

not facing condition compared to the **facing** condition (Table 5b). Therefore, we will look at the *T8* channel for the **void to identification** condition.

As was mentioned in section 3.2.3, the ending of the **shift-of-focus** condition might contain inter-brain synchrony values that are not part of the **shift-of-focus** condition. For this reason, there is a black vertical dashed line in Figures 7a to 7d and 8c and 8d.

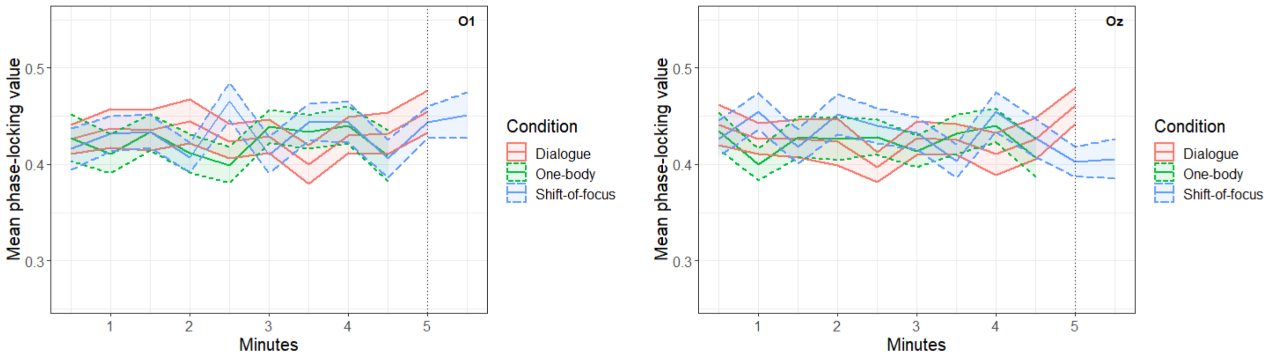
Channels for the *beta* band will not be considered for further analysis for the professional dancers, since none of the results of the laboratory experiment survived the p-value correction.

4.2.1 Inter-brain synchrony

Above the reasoning behind the channels of interest was discussed. In this section, the visualised inter-brain synchrony measures for the channels of interest are presented and discussed in relation to the findings of the laboratory experiment. After discussing the visualizations for the *theta* and *alpha* frequency band, we will compare the inter-brain synchrony measures. We do have to note that the Figures presented in this section contained binned data from the complete EEG recordings of the relevant conditions and cities. The beginning and ending of the EEG data might not be directly the start and ending of the conditions (see Methods).

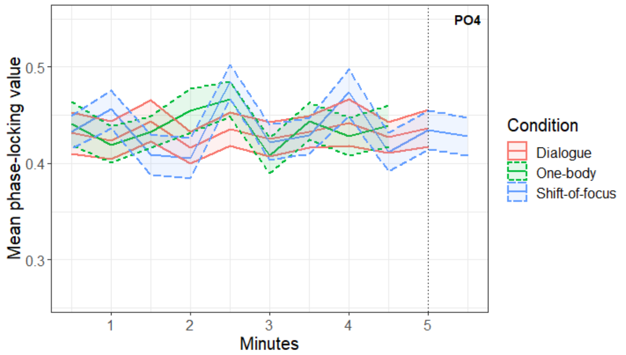
Theta frequency band [4-9 Hz]. The mean PLV for the **one-body** and **shift-of-focus** condition seems to fluctuate around 0.43 for the *O1* channel (Figure 7a), *Oz* channel (Figure 7b) and the *PO4* channel (Figure 7c). The mean PLV peaks in the **shift-of-focus** condition around 2.5 minutes for both the *O1* and the *PO4* channel. An opposite effect is visible for the **one-body condition** where the mean PLV peaks around 2.5 minutes in the *PO4* channel, where the mean PLV for the *O1* channel reaches a minimum. In addition, the mean PLV appears to fluctuate more for the **shift-of-focus** condition compared to the **dialogue** condition. There appears not to be a clear distinction between the **one-body** and the **shift-of-focus** condition. In the laboratory experiment, the mean PLV was on average around 0.43 for the **one-body** condition for all three channels and around 0.42 for the **shift-of-focus** condition (Table 4). However, if we look at the mean PLV for the **one-body condition** of the professional dancers, the average is around 0.44 (SD = 0.11) for the *PO4* channel, 0.42 (SD = 0.11) for the *Oz* and the *O1* channel. For the **shift-of-focus** condition, the mean PLV are on average around 0.44 (SD = 0.11) for the *PO4* channel, 0.43 (SD = 0.1) for the *Oz* and the *O1* channel. The mean PLV for the professional dancers appears to show an opposite effect for the **one-body** and **shift-of-focus** condition compared to the laboratory experiment. Where the mean PLV on average is higher for the **shift-of-focus** condition in comparison to the **one-body** condition. Notable is that the mean PLV for the *PO4* channel is on average around 0.44 for both conditions in comparison with a significant difference between the two conditions in the laboratory experiment.

Figure 7d illustrates the imaginary coherence for the **dialogue** and **shift-of-focus** condition in the *FP1* channel. The imaginary coherence for both conditions fluctuates around 0.53 and there appear to be no notable differences in imaginary coherence between the two conditions. The only difference appears to be towards the end of both conditions around the vertical line. In the laboratory experiment, the average imaginary coherence for the *FP1* channel for the **dialogue** condition was around 0.63, whereas the average imaginary coherence for the **shift-of-focus** condition was around 0.64. Where the imaginary coherence was significantly lower in the **dialogue** condition in the laboratory experiment, the average imaginary coherence for the professional dancers is for both conditions around 0.54 (SD = 0.04). These average are considerably lower compared to the average from the laboratory experiment. However, the imaginary coherence was transformed using the Fisher's z transformation (See section 3.2.3). Consequently, the average imaginary coherence for the professional dancers is

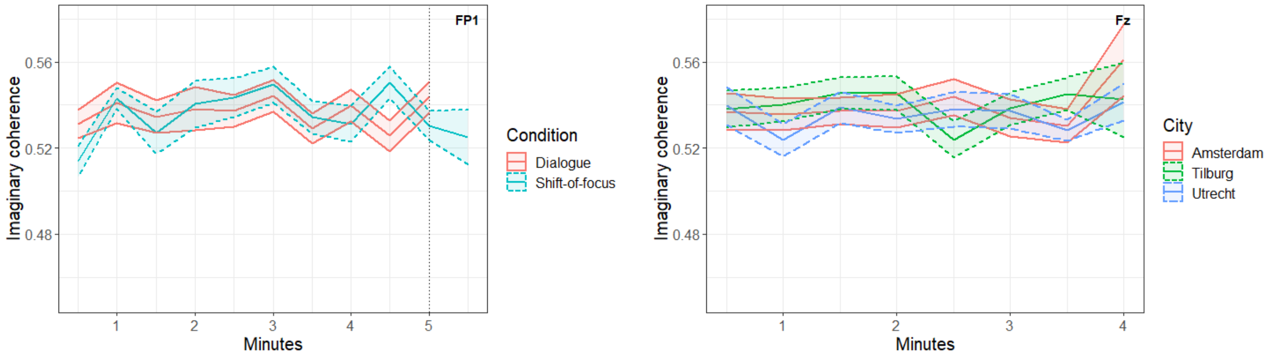


(a) Mean phase-locking value (**O1**).

(b) Mean phase-locking value (**Oz**).



(c) Mean phase-locking value (**PO4**).



(d) Imaginary coherence (**FP1**).

(e) Imaginary coherence (**Fz**).

Figure 7: Inter-brain synchrony on the *theta* band 4-9 Hz for the professional dancers over time. (a) (b) (c) Mean phase-locking value (O1, Oz, PO4) for the **dialogue**, **one-body** and **shift-of-focus** conditions. (d) Imaginary coherence (FP1) for the **dialogue** and **shift-of-focus** conditions. (e) Imaginary coherence (Fz) for the **tendus to mechanical** condition. The black dashed vertical line is to indicate a possible different condition to the shift-of-focus condition. The coloured areas around the lines indicate the standard error.

lower compared to the average imaginary coherence of the laboratory experiment. Where the average imaginary coherence was significantly higher in the **shift-of-focus** condition, the average imaginary coherence is equal for the professional dancers.

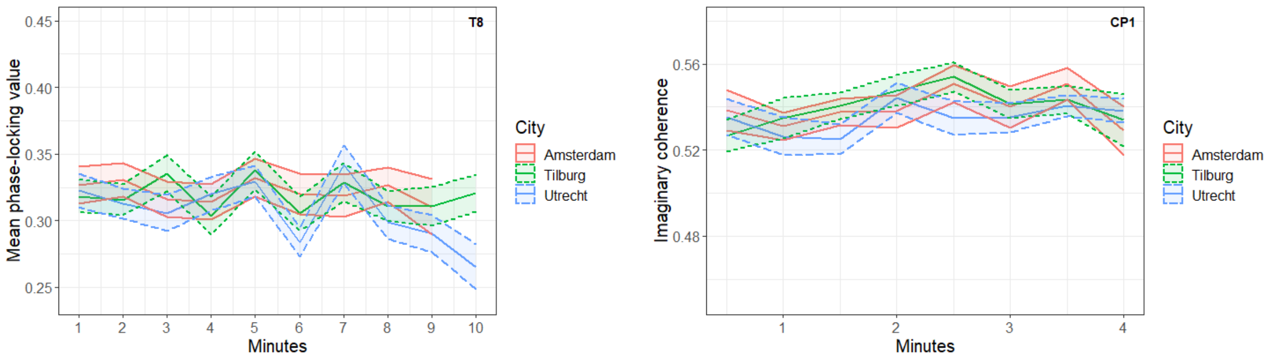
In Figure 7e we see that the imaginary coherence for the three performances moves around 0.54 for the **tendus to mechanical** condition in the *Fz* channel. The imaginary coherence are on average 0.54 for the Amsterdam and Tilburg performance and 0.53 for the Utrecht performance with $SD = 0.04$. These averages are similar to the averages for the *FP1* channel in the **dialogue** and **shift-of-focus** conditions (Figure 7d). It is striking that the imaginary coherence on average is approximately equal for various conditions, channels and performances.

The mean PLV for the *theta* frequency band from the professional dancers seems to be in the same range as the mean PLV from the laboratory experiment. However, even though the values are in the same range, the same trends are missing. The same accounts for the imaginary coherence in the *FP1* channel were a clear distinction between the two conditions is missing.

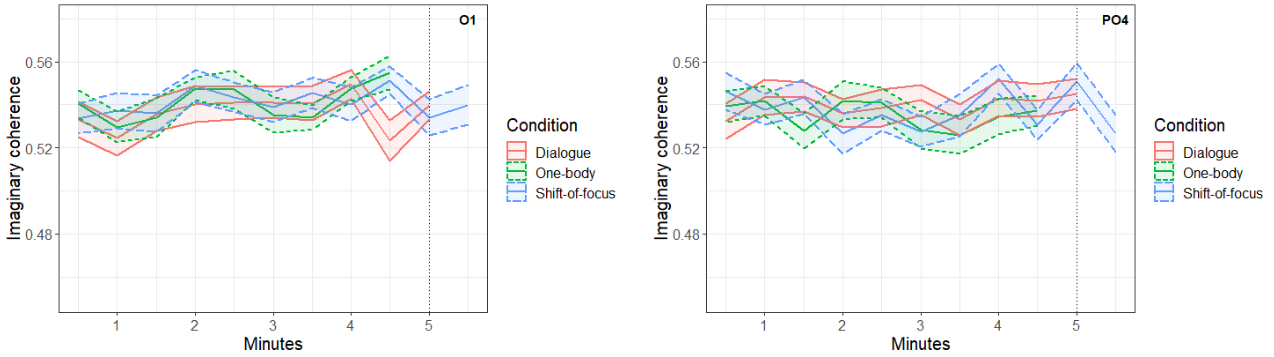
Alpha frequency band [9-14 Hz]. In the laboratory experiment, we saw that there was significantly more inter-brain synchrony in the T8 channel when the dyads were moving when they were not facing each other compared to moving face-to-face. The professional dancers were dancing while not facing each other in the **void to identification** condition. Figure 8a shows the mean PLV for the T8 channel over time for the three cities. There was not a specific facing condition for the professional dancers to which these results can be compared. Thus, the average mean PLV for the T8 channel from the various performances from the professional dancers will be compared to the average mean PLV from the laboratory experiment. In the laboratory experiment, the average mean PLV was 0.33 (Table 5b) for when the dyads were engaged in joint movement while not facing each other. The mean PLV is on average 0.32 (SD = 0.11) for Amsterdam, for Tilburg 0.32 (SD = 0.1) and for Utrecht 0.31 (SD = 0.1). These values correspond more with the average mean PLV when the dyads are engaged in joint movement face-to-face. Figure 8a shows that the mean PLV for Utrecht seems to fluctuate more compared to the mean PLV of the other two cities. Moreover, towards the end, the mean PLV for Utrecht declines more compared to the mean PLV of the other two cities. In addition, the mean PLV for Utrecht is on average slightly lower compared to the average mean PLV for the other two cities.

For the **tendus to mechanical** condition, the professional dancers were engaged in synchronized movement. The imaginary coherence for the *CP1* channel for the Amsterdam, Tilburg and Utrecht performance is depicted in Figure 8b. As was explained in the previous paragraph, the imaginary coherence here was calculated with the transformation which resulted in lower imaginary coherence compared to the imaginary coherence calculated without the transformation. There appear to be no distinctive differences between the imaginary coherence for the three performances. The average imaginary coherence for Amsterdam and Tilburg are 0.54 and for Utrecht 0.53 all with $SD = 0.04$. It is noteworthy that the average inter-brain synchrony values for the Utrecht performance are lower compared to the averages of the other two cities for the *Fz*, *T8* and *CP2* channels.

Where there was a significant difference in the mean PLV between the **one-body** and **shift-of-focus** conditions for the *O1* and *PO4* channel in the *theta* band, the same was true for the imaginary coherence in the *alpha* band for the laboratory experiment. Figures 8c and 8d illustrate the imaginary coherence for these same channels and conditions only for the professional dancers. Similar to the mean PLV (Figures 7a and 7c) there is no noticeable difference between the **shift-of-focus** condition compared to the **one-body** condition for either the *O1* or the *PO4* channel. Similar to the results for the *FP1* channel in the *theta* band, the difference in imaginary coherence seems to be towards the end around the vertical line. The imaginary coherence is on average for both the *PO4* and *O1* channels and both conditions 0.54 (SD = 0.04).



(a) Mean phase-locking value (**T8**). (b) Imaginary coherence (**CP1**).



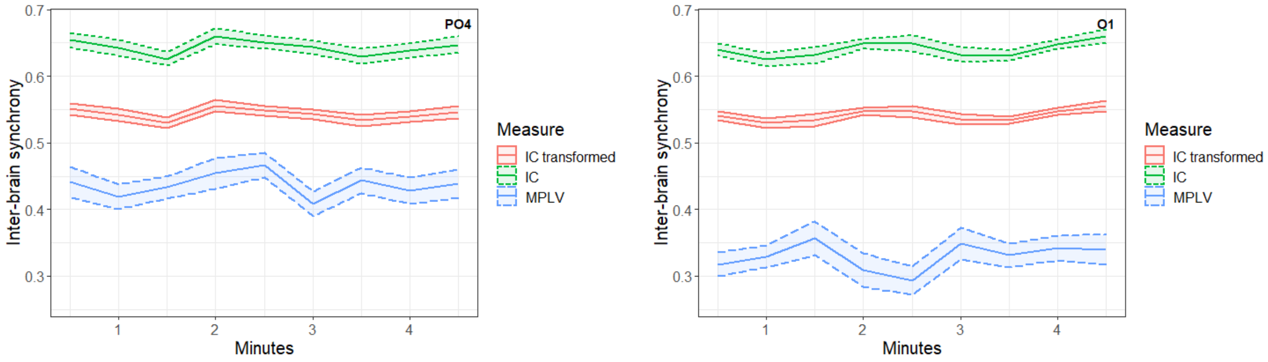
(c) Imaginary coherence (**O1**). (d) Imaginary coherence (**PO4**).

Figure 8: Inter-brain synchrony in the *alpha* band 9-14 Hz for the professional dancers over time. (a) Mean phase-locking value (T8) for the **void to identification** condition for the three different cities. (b) Imaginary coherence (CP1) for the **tendus to mechanical** condition for the three different cities. (c)(d) Imaginary coherence (O1, PO4) for the **dialogue**, **one-body** and **shift-of-focus** conditions. The black dashed vertical line is to indicate a possible different condition to the shift-of-focus condition. The coloured areas around the lines indicate the standard error.

The trends for the **one-body** and the **shift-of-focus** conditions do not seem to uphold for the imaginary coherence in the *O1* and *PO4* channel for the professional dancers. The mean PLV for the **tendus to mechanical** condition in channel *T8* seemed to be more in line with the values of the face-to-face condition in the laboratory experiment.

4.2.2 Comparing Inter-brain synchrony measures

The inter-brain synchrony measures so far have been compared in various social and nonsocial conditions. Figures 9a and 9b portray three inter-brain synchrony measures for the **one-body** condition of the Amsterdam performance. Figures 9a and 9b compare the mean PLV, imaginary coherence (IC) and imaginary coherence transformed (IC transformed). In section 3.2.3, an altered method for calculating the imaginary coherence was discussed. The imaginary coherence transformed is the imaginary coherence calculated using Fisher's Z transformation. Imaginary coherence is calculated without the transformation similar to the way it was calculated in the laboratory experiment. The Figures 9a and 9b show that the imaginary coherence measures stay around 0.64 and 0.54 for the transformed imaginary coherence for both channels and frequency band. The mean PLV for the *PO4* channel in the *theta* band is noticeably higher compared to the mean PLV for the *O1* channel in the



(a) *Theta* band 4-9 Hz (b) *Alpha* band 9-14 Hz.

Figure 9: The inter-brain synchrony measures over time for two different channels and two different frequency bands for the **one-body condition** in the Amsterdam performance. The graphs show imaginary coherence transformed by Fisher's z transformation (IC transformed), imaginary coherence determined without the transformation (IC) and the mean phase-locking value (MPLV). (a) Inter-brain synchrony for the *PO4* channel. (b) Inter-brain synchrony for the *O1* channel. The coloured areas around the lines indicate the standard error.

alpha band. Both imaginary coherence with and without transformation are more stable and fluctuate less compared to the mean PLV in both channels and frequency bands. Where the mean PLV appears to vary over various conditions and channels, the transformed imaginary coherence stays around 0.54 for most channels and conditions seen in this section. Even though the mean PLV varies, the imaginary coherence both with or without transformation are higher compared to the mean PLV.

5 Discussion

The goal of this thesis was to investigate whether there is a universal way to connect. Two research questions were defined. The first question is about whether the feeling of social connectedness could be induced through dance-like movements. For the second question, we wanted to examine whether inter-brain synchrony is an indicator of the subjective report of social connectedness. To answer these two research questions, we will discuss the findings from the laboratory experiment and the moving in the wild experiment. Next, the limitations of the current study will be discussed after which we will discuss possibilities for continuing this line of research and topic.

5.1 Findings

For the laboratory experiment several sub-questions were formulated (Table 2). These sub-questions were created in support of answering the two main research questions. In the coming sections, the sub-questions will be examined in light of the findings. In section 5.1.1 we will answer the question of whether dyads subjectively experience feeling more mentally/physically connected while moving in the social conditions compared to the nonsocial conditions. In the next section, 5.1.2, we will discuss whether moving in various social and nonsocial conditions induces inter-brain synchrony. In section 5.1.3, the following question will be answered; " Is feeling mentally/physically connected to a partner associated with inter-brain synchrony while controlling for conditions?" The last question about the effect of modulating factors on inter-brain synchrony will be discussed in section 5.1.4. Finally, in section 5.1.5 the results from the moving in the wild experiment will be discussed.

5.1.1 Subjective experience during movement

We predicted that dyads would report feeling more connected when they moved in the social conditions compared to the nonsocial conditions. The results of the subjective ratings analysis were partially in agreement with our predictions. The subjective ratings, for both mental and physical connection, of the social conditions were significantly higher compared to the subjective ratings from the nonsocial conditions for almost all condition pairs (Figure 1). If dyads were engaged in joint movement while facing, they reported feeling more connected compared to not facing. Moreover, when dyads are moving like being in a dialogue they also feel more connected compared to moving while shifting-the-focus away. Lastly, moving like one-body also makes dyads report feeling more connected in comparison to both the shift-of-focus condition and the alone condition.

Surprisingly, there was not a significant difference between the average subjective ratings of feeling more mentally or physically connected in the synchronous condition compared to the asynchronous condition. This finding is not in line with the findings of previous research. For example, Reddish et al. (2013) found that moving in synchrony affects feeling socially connected compared to moving asynchronously. We found that whether dyads are facing each other while moving affects the feeling of connectedness more compared to moving synchronously or asynchronously. The average subjective ratings for the facing and synchronous conditions consisted of combined ratings. For example, the subjective ratings for the **facing** condition consisted of ratings from both the **asynchronous facing** condition and the **synchronous facing** condition. Figure 11 in appendix E visualizes the average subjective rating for the uncombined conditions. The **synchronous facing** condition does have the highest average subjective ratings for both mental and physical connection. However, the results of the paired t-test proved that when the dyads were engaged in joint movement, whether they were facing each other was of significant influence on the subjective experience of connectedness.

The average rating is in most conditions higher for mental connectedness in comparison to physical connectedness. The exception is for the one-body condition where the average physical connectedness rating is higher than the average rating for mental connectedness. A possible explanation for this is that the one-body condition is the only condition where the dyads could touch each other. This suggests that the touch effect is of key importance in the subjective experience of physical connectedness.

The dyads reported feeling the most mentally connected in the dialogue condition according to the average subjective ratings. The partners had to interpret and respond to each other through movement. They needed to focus on what the other one implied with the movements and how to respond accordingly. The dialogue condition strongly contains aspects of non-verbal communication. There is a message behind the movements. Non-verbal communication is of key importance in social interaction. For example, non-verbal communication can confirm the message someone is trying to convey, however, it can also contradict the message someone is trying to convey. (Phutela, 2016).

5.1.2 Inter-brain synchrony during movement

The previous section showed that moving in various social conditions can induce a subjective experience of connectedness. We predicted that moving in social conditions would induce more inter-brain synchrony compared to nonsocial conditions. We hypothesized that inter-brain synchrony could occur in various brain areas and in one of the following three frequency bands; the *theta* [4-9 Hz], *alpha* [9-14 Hz], and *beta* [14-28 Hz] band. Two different inter-brain synchrony measures were adopted, the mean phase-locking value (mean PLV) and the imaginary part of coherence. The results showed there was indeed a significant difference in inter-brain synchrony between various conditions in the *alpha* and *theta* band. However, both inter-brain synchrony measures did not yield the same results.

Mean phase-locking value. The results for the mean PLV in the *theta* band were in line with our predictions. There was more inter-brain synchrony in the parietal-occipital area for the **one-body** condition compared to the **shift-of-focus** condition (Figure 2a). Dumas et al. (2010) found significant inter-brain synchrony in the parietal-occipital area during joint action, however, this was for the *beta* oscillations and not for the *theta* oscillations. Balconi and Fronda (2020) did find an increase in inter-brain synchrony in the *theta* band in the posterior (parietal) area between an encoder and decoder engaged in exchanging informative gestures. Balconi and Fronda argue that the increase in inter-brain synchrony in the posterior area can be explained by the involvement of perceptual processes in observing and executing informative gestures. In the **one-body** condition, the dyads need to move as a unity which means carefully observing the movements of the partner and executing movements accordingly. This is in agreement with how Clarke (1994) describes the function of the parietal area which is responsible for processing somatosensory information from the body. It is about merging perceptual information with sensory and motor information. Even though moving while shifting-the-focus away from a partner also involves planning and execution of movements, the partner and their movements do not need to be observed and reacted to. The findings suggest that there is an increase in inter-brain synchrony when dyads are engaged in moving as **one-body** compared to **shifting-the-focus** away. However, the three channels are close in proximity. The results could be due to volume conduction which is a possibility with the mean PLV (Lachaux et al., 1999). This is just speculation as we cannot tell whether this is indeed the case and what is the source of the activation.

Furthermore, the mean PLV was higher in the *alpha* band for a nonsocial condition, **not facing**, compared to a social condition, **facing**. There was more inter-brain synchrony in the right temporal area (Figure 2b) in the **not facing condition**. Although we did not predict to see more inter-brain synchrony in a nonsocial condition, there is a possible explanation for this finding. The temporal area is known for processing auditory information. When the dyads were not facing they were engaged in either synchronous or asynchronous movement. The metronome beat becomes more critical to move in synchrony or asynchrony. Even though we argued that the metronome sound itself would not affect our statistical analysis, this could be an indication that dyads were more focused on the metronome sound to move in synchrony or asynchrony when they were not facing each other.

Imaginary coherence. The results for the imaginary coherence in the *alpha* band showed that there was more inter-brain synchrony in the occipital area in the **shift-of-focus** condition compared to the **one-body** condition (Figure 3). These findings contradict our predictions and also the findings in the *theta* band. Namely, here there is more inter-brain synchrony in the **shift-of-focus** condition which is a nonsocial condition. It is noteworthy that there is more inter-brain synchrony in the occipital area in the condition where the visual focus of the participants is directed away from their partner. The occipital area is known for object and face recognition, distance and depth perception and colour determination (Rehman & Khalili, 2021), amongst others. This finding does suggest that when dyads have to actively shift their focus away from their partner this still can induce inter-brain synchrony. The reason for this could be the fact that the dyads had to actively shift their visual attention towards something else. Goldstein et al. (2018) found in their control condition, where there was no touch and no pain administered, inter-brain couplings between the occipital areas. They explained them by resting visual alpha activations. However, the **shift-of-focus** condition is not comparable to a resting state.

The final result for the imaginary coherence discovered that there was more inter-brain synchrony in the central parietal area in the **synchronous** condition compared to the **asynchronous** condition (Figure 3). Where the subjective reports of connectedness did not show a significant difference between these two conditions, the imaginary coherence did uncover significant differences in inter-brain synchrony. These results are in line with our predictions and also the findings of other studies. For example, Dumas et al. (2010) found significant inter-brain synchrony in the right parietal area during joint movement in the *alpha* band. Moreover, Hu et al. (2018) discovered during a cooperation task, that there was significant inter-brain synchrony in the central parietal area in the alpha oscillations. The central electrodes could be said to cover the premotor cortex, which is suspected to contain the location of the human mirror neuron system according to Rizzolatti (2005) as cited by Sänger et al. (2012). The finding could indicate that synchronous movement elicits activation of the mirroring system.

Inter-brain synchrony measures Dumas et al. (2010); Dikker et al. (2021) both found significant inter-brain synchrony in the beta frequency band, whereas the results for the laboratory experiment did not show any significance concerning the beta band. At least none of the results survived the p-value correction. Both Kinreich et al. (2017); Goldstein et al. (2018) also investigated the *beta* band but did not find significant results. These results suggest that movement in various social and nonsocial conditions elicits inter-brain synchrony in the *theta* and *alpha* bands but not in the *beta* band.

We also looked at whether the mean PLV and the imaginary coherence were correlated. We did not find that the two measures were correlated to one another. Whether the two measures are correlated is also not something reported in the discussed literature. Since we did not find the same results and the measures appear not to be correlated, this suggests that the mean PLV and imaginary coherence cannot be used interchangeably. The phase synchrony measures could be used in complement to each other.

To conclude, the results suggest that movement in various social and nonsocial conditions can elicit inter-brain synchrony. For both inter-brain synchrony measures, the **one-body** vs. the **shift-of-focus** conditions are the most noteworthy conditions.

5.1.3 The subjective experience and Inter-brain synchrony

The previous sections showed that based on the subjective ratings, dyads do experience feeling more socially connected in most of the social conditions compared to the nonsocial conditions. In addition, there was inter-brain synchrony in various social and nonsocial conditions. Besides investigating the subjective experience and the inter-brain synchrony separately, we also investigated whether the subjective experience affected the inter-brain synchrony. The dyads were subdivided into three possible groups for each condition based on the average subjective ratings for each participant in a dyad and the difference between the average ratings within a dyad. The results did not uncover a relationship between the subjective experience of connectedness and moving in various social and nonsocial conditions. With the mean PLV, we did uncover a significant effect for the *theta* band in the frontal area. Namely, there was more inter-brain synchrony in the group that experienced feeling the most connected on average compared to the group where the dyads had a large discrepancy in their subjective experience of connectedness (Figure 4a). For the imaginary coherence in the *alpha* band, on the other hand, we found the opposite result. Here we saw there was more inter-brain synchrony in the anterior-frontal area for the rating group with a high difference compared to the high average rating group (Figure 4b). Even though both measures found opposing results, they do suggest that there could be a relationship between the subjective experience of connectedness and inter-brain synchrony in the (anterior) frontal areas.

However, the current setup does not seem to support the claim that when dyads report to experience more connectedness, this is associated with inter-brain synchrony. A possible explanation for this is that the dyads were subdivided into one of three possible groups for the subjective ratings. The groups were *high average*, *high difference* and *low average*. The two-way mixed ANOVA models first looked at the effect of the condition on the inter-brain synchrony measures, after which it investigated the relationship between the inter-brain synchrony measures and the subjective ratings. Important to note is that the division of the subjective rating groups is strongly related to the conditions. Take, for example, the subjective ratings in the **dialogue** condition. 80% of the dyads were placed in the *high average* rating group and 20% of the dyads in the *high difference* rating group. Thus, when accounting for the effects of conditions first, this might also take away the possible effect of the rating groups on inter-brain synchrony.

5.1.4 Modulating factors on Inter-brain synchrony

Several studies found factors that affected inter-brain synchrony. For example, the gender of the participants the gender of the participants (Cheng et al., 2015; Pan et al., 2017), the relationship between the participants (Kinreich et al., 2017; Pan et al., 2017) and also how well the participants knew each other (Dikker et al., 2021). For these reasons, we also investigated whether the gender, frequency of contact and closeness of the relationship affected the inter-brain synchrony.

For the *theta* band, the relationship between the dyads affected the imaginary coherence in the (anterior) frontal area (Figure 5a and 5b). Where we predicted that a close relationship would lead to more inter-brain synchrony, this was not the case in the **dialogue** and **synchronous** conditions. In these social conditions, the imaginary coherence was higher for the dyads that did not have a close relationship. Moreover, for the closely related dyads, the imaginary coherence was higher in the **shift-of-focus** condition, a nonsocial condition, compared to the **dialogue** condition. Similarly, closely related dyads also showed more inter-brain synchrony moving asynchronously compared to moving in synchrony. Lastly, dyads that did not have a close relationship did show more inter-brain synchrony in the social, **dialogue** condition, compared to the nonsocial, **shift-of-focus** condition. Sänger et al. (2012) also found inter-brain synchrony in the frontal area in the *theta* band during guitar playing duets. According to them, it supports the idea that the frontal areas are involved during interpersonal action coordination. Sänger et al. (2012) also raise the idea that this might be due to the high demand on musical coordination. There is a possibility that the inter-brain synchrony for dyads that are not closely related is due to the effort that is needed to understand the other person.

For the *alpha* band, we found that the relationship affected the mean PLV in the **facing** vs. **not facing** condition in the right central area (Figure 6b). The mean PLV was higher in the **not facing** condition for the dyads that were not close compared to those that are close. In addition, the mean PLV in the **not facing** condition was also higher than the **facing** condition for the dyads that were not close. In section 5.1.2, we saw that there was more inter-brain synchrony in the not facing condition in the T8 channel. The C4 and the T8 channel are close in proximity. There is a possibility that this finding could be caused by volume conduction. Once again, this is just speculation. There was also a significant effect of gender on the imaginary coherence in the parietal-occipital area in the **one-body** vs. **shift-of-focus** condition (Figure 6a). For the dyads of the same gender, the imaginary coherence was lower in the **shift-of-focus** condition than the imaginary coherence of dyads that were not of the same gender. This result is not in line with our prediction. The result that was in line with our predictions is that for dyads of the same gender, the imaginary coherence was higher in the **one-body** condition compared to the **shift-of-focus** condition.

Even though some of the results are in line with our predictions, there are some concerns with the modulating factors. First, the gender of the dyads was not balanced since 32% of the dyads had the same gender. This resulted from the fact that the laboratory experiment was not designed to account for these factors. Moreover, for analysis, the dyads were also divided into two groups based on the closeness of the relationship and the frequency of contact. We tried to create balanced groups and had to decide which relationships would be considered close. Spouses/couples were considered to have a close relationship, whereas colleagues and friends were not considered close. This resulted in 44% of the dyads being in the *close* relationship group and 52% of the dyads in the *frequent* contact group. Our interpretation of closeness and frequency of contact is debatable. Another point of attention is that the three modulating factors are correlated. For example, the spouses were mixed gendered and they saw each other every day. So, these dyads were not in the same gender group, they were in the close relationship group and the frequent contact group.

Having said that, our findings are consistent with the literature which suggest that the gender and the relationship of participants can affect inter-brain synchrony. Nonetheless, the differences in inter-brain synchrony between the groups were fairly small.

5.1.5 Moving in the wild

The moving in the wild experiment was to explore various ways of connecting with oneself and with each other through movement. The experiment showed that trying to record brain activity while moving in an uncontrolled environment comes with its difficulties. The performance was done in several cities, however, only data from three cities could be used. There were two reasons for this. First, some of the electrodes came off during some of the performances. In addition, the data that remained for the two dancers contained quite some noise. For analyzing the results from the professional dancers, we decided to use the results from the laboratory experiment to narrow down the number of channels to look at. The trends that were visible in the laboratory experiment did not seem to uphold for the professional dancers. There are, however, some concerns with this approach. Even though the conditions were the same in concept, the execution was completely different. Were the professional dancers were free to move, the dyads in the laboratory experiment had to confine their movements to arm and hand movements only. Where the dyads in the laboratory experiment moved to the beat of a metronome, the performance of the professional dancers was accompanied by live composed music. For the laboratory experiment, we took into account the possible effect of the sound of the metronome on inter-brain synchrony. This was not done for the inter-brain synchrony of the professional dancers. But then, the music was also less consistent compared to the metronome beat.

The visualization of the inter-brain synchrony measures of the professional dancers did allow us to take a closer look at the behaviour over time. The imaginary coherence does appear more stable and less variable over time in comparison to the mean PLV (Figure 9a and 9b). This is in agreement with the findings by Nolte et al. (2004). It is less sensitive but because of this, it might also miss synchronization. Moreover, the transformed imaginary coherence appears even less variable and more constant compared to the original imaginary coherence. Even though Fisher's Z transformation has been used in other studies (Englot et al., 2015; Hinkley et al., 2011; Rolston & Chang, 2017), it might not have been the most suitable transformation for the current data. More about this will be discussed in the next section.

The channels from the professional dancers that were considered were based on the results of the laboratory experiment. We assumed that the synchronization of brains during movement might be the same for professionals and novices. Since the objective here is to investigate whether there is a universal way to connect, would this matter? Fink, Graif, and Neubauer (2009) investigated creative thinking between professional dancers and novice dancers. They found a significant difference in the alpha oscillations, within a brain between the professionals and the novices. The professional dancers showed significantly more *alpha* synchronization in the parietal regions than the novices. So, perhaps professional dancers might connect differently compared to novices.

Even though the trends from the laboratory experiment did not uphold for the data from the professional dancers, their performances laid the groundwork for the laboratory experiment and exploring various ways of connecting through movement.

5.2 Limitations

In the previous sections, possible limitations were discussed. Here we will discuss the broader limitations of this thesis.

To begin with, the two inter-brain synchrony measures, the mean PLV and the imaginary coherence. Both measures discovered different findings (e.g. Figure 2a and Figure 3). This could support the idea that inter-brain synchrony measures cannot be used interchangeably but need to be used in complement to each other. It does make the interpretations of the results more difficult when there appear to be contradictions. There is a possibility that some of the results for the mean PLV are due to volume conduction, as was discussed in the theoretical framework. Therefore, we decided to use the imaginary coherence beside the mean PLV. Bornot, Wong-Lin, Ahmad, and Prasad (2018), amongst others, stated that even though the imaginary coherence is robust to the effects of volume conduction, it does have two issues. The first is that the imaginary coherence ignores the real part of coherence. The consequence is that when there is true synchronization with zero or π phase, this is not flagged as synchronization by the imaginary coherence. The second issue is that the normalization used by Nolte et al. (2004) is unstable. In the laboratory experiment, we noted that the average imaginary coherence values were quite a bit higher compared to the mean PLV. Consequently, we used Fisher's z transformation to transform the imaginary coherence values from the professional dancers. This resulted in lower imaginary coherence values on average compared to before the transformation. However, the transformed imaginary coherence values seemed even more stable and less variable compared to the imaginary coherence values that were not transformed. Domínguez, Stieben, pérez Velázquez, and Shanker (2013) also used the imaginary part of coherence to investigate differences in cortical functional connectivity between preschool children with Autism Spectrum Disorders to those without. They argued that the absolute imaginary coherence linearly depends on the standard deviations. Therefore Domínguez et al. (2013) used the inverse transform for each data point. Since the values were all quite high and we were mainly investigating whether there were significant differences between conditions, we do not think the imaginary coherence here is incorrect. We do believe the imaginary coherence measure used, could have been improved upon by using a different normalization technique.

The limitations described by Reddish et al. (2013) are also applicable to the experiments outlined in this thesis. Reddish et al. argue that when humans are dancing in a natural setting it lasts longer than a mere few minutes. The conditions in the laboratory experiment lasted for two minutes. For the professional dancers, the **void to identification** condition lasted around ten minutes, however, the other conditions only lasted half that long. So, it could be that the two minute windows for the laboratory experiment were too short for exploring connection in more depth.

We argued that the metronome beat would not affect the inter-brain synchrony since the metronome beat transformed to the frequency domain (1.33 Hz) was lower than the lowest frequency we would look at (4 Hz). However, the harmonics of the metronome beat could still be of influence. The exclusion of the frequency in the brain activity does not exclude the effect the metronome beat has on the participants and their behaviour. For example, Teramoto et al. (2012) showed that the interpretation of visual motion could be affected by sound. According to Teramoto et al., their findings suggested that auditory and visual modalities can influence each other considering motion processing. Even though their study involved the discrimination of the direction of a square, it still showed that the perceived direction of this square could be affected by sound. Thaut, Kenyon, Schauer, and McIntosh (1999) described their findings by stating that the motor system was sensitive to auditory priming and timing. The explanation Thaut et al. (1999) provided was considering the evolutionary function of this phenomenon. Namely, using auditory information would possibly enhance the control and organization of motor action, especially considering time. We cannot ignore the possibility that the metronome beat might have influenced the participants in their (motor) actions.

Data from six dyads was missing in the **alone** condition. During the analysis, we removed the data from the same dyads in the **dialogue** condition. For these two conditions data from 19 dyads remained. We created a model for each channel separately and we had to use the data up until trial 90 because not for all dyads and conditions there was data for 120 trials. This does not leave much data which was a possible reason for the overfitting of the linear mixed-effects models. Hence, we opted to use ANOVA instead. For the ANOVAs we had to average over the trials. By averaging, the effects that unfold over time are lost. This does make the results that we found noteworthy but there could also be effects that are were lost in the process of this statistical analysis.

The final limitation was already partially discussed in the section about the modulating factors on inter-brain synchrony. We tried to create balanced groups for analyzing the effect of the relationships and the frequency of contact. However, we made assumptions in deciding what could be considered as a close relationship and what could be considered a frequent contact. Another issue with balanced groups was the division of dyads into subjective rating groups. Were an analysis and grouping about certain factors can be considered in advance, the subjective ratings cannot be considered in advance. The differences that we found between the modulating factors and the inter-brain synchrony that were significant were small. We cannot exclude the possibility that these results are because the modulating factors indeed affect inter-brain synchrony and are thus also in agreement with the literature. There is also a possibility that these findings are caused by the current experimental setup. Possible solutions for this will be discussed in the next section.

5.3 Future work

In this section, several ideas for the continuation of this project will be discussed. First, in the previous section, we mentioned the issue with grouping the dyads based on the subjective ratings. A possible solution for this would be the use of cluster analysis. With cluster analysis, the goal is to group items into clusters that are closely associated with each other. Several techniques could be considered for grouping the subjective ratings with the inter-brain synchrony of the dyads. For cluster analysis, it is crucial to have sufficient data to train and test the algorithm. The current data from the laboratory experiment is most likely insufficient for successfully training and testing a cluster-based algorithm.

We found inter-brain synchrony in various social and nonsocial conditions for the *alpha* and *theta* bands. We also looked at the *beta* frequency band but none of the results survived the p-value correction for the multiple comparison problem. Research investigating inter-brain synchrony during social interaction recorded other frequencies as well. For example, Kinreich et al. (2017) found inter-brain synchrony in the *gamma* oscillations in the temporal-parietal area for couples and not for strangers. In addition, Dumas et al. (2010) also found inter-brain synchrony in the frontal-central and parietal region for the gamma frequency band. The *gamma* band could be considered next to the *alpha*, *theta*, and *beta* frequency band. Sänger et al. (2012) discovered significant inter-brain synchrony in the frontal and central areas in the *delta* oscillations. However, as was discussed in the Methods section, the frequency from the metronome beat was approximately 1.33 Hz. The delta band contains oscillations in the range of [0.5, 4 Hz]. Hence, for future work caution should be taken in considering analyzing the *delta* band for this data.

For the analysis of the inter-brain synchrony, we only considered the same channels for each participant in a dyad. However, other studies have compared multiple channels from other participants, not just the same channels. For example, Goldstein et al. (2018) found that inter-brain synchrony was between different regions of the receiver of pain and the observer of the pain. Namely, there were couplings between the central regions of the pain target's brains to the right hemisphere of the observer's brains. Furthermore, Mu et al. (2017) compared multiple electrodes for investigating the role of the gamma oscillations in inter-brain synchrony during a social coordination task. Apart from looking at only the same channels, all the channels between participants could be considered. This would, however, increase the computation time significantly. Moreover, it would also increase the difficulty of interpreting these results, if synchrony means that brains work in similar ways.

The moving in the wild experiment showed the difficulties that can arise when people try to explore the connection in a more naturalistic setting. For example, electrodes that came of during the dance performance. In addition, the data that remained for the dancers also contained quite some noise. To experiment with a more naturalistic setting was also the main objective of the research done by Dikker et al. (2021). The laboratory experiment did result in significant findings even after correcting for the multiple comparison problem. Even though Dumas et al. (2010) and Balconi and Fronda (2020) showed that mere hand movements and gestures are sufficient to elicit inter-brain synchrony, it would be interesting to explore connection through dance in an even more naturalistic setting. Additionally, in this naturalistic setting, the participants should not have to confine their movements. Part of the solution would be to look at more portable and easier accessible EEG recording systems. Hinrichs et al. (2020) investigated the workings of a wireless dry electrode EEG system with a wired wet electrode EEG system. They concluded that the portability, signal quality and ease of set-up of the wireless dry electrode EEG headset complied with the needs of clinical applications. So, this suggests the possibility that future work could be done in more naturalistic settings with the help of wireless portable EEG systems.

6 Conclusion

This thesis aimed to find out whether there is a universal way to connect. In the introduction, we mentioned two broad research questions. First, can dance-like movement induce the feeling of social connectedness? The results showed that moving in various social conditions did elicit the feeling of both mental and physical connection. Where moving as one-body with the possibility of physical contact led to feeling the most connected in a physical sense. Moreover, moving face-to-face, irrespective of synchronous or asynchronous movement, also lead to the feeling of connection both on a physical and mental level. Lastly, movement as if one was in a dialogue, almost representing non-verbal communication, lead to feeling the most connected on a mental level. The second question was, is inter-brain synchrony a measure for the subjective report of social connectedness? To answer this question, we created several sub-questions. The two different inter-brain synchrony measures discovered significant differences between the inter-brain synchrony in various brain areas between the social and nonsocial conditions. These results were found in both the *theta* and *alpha* oscillations. However, our results did not expose a significant relationship between the subjective experience of social connectedness and inter-brain synchrony. Lastly, we found that the closeness of the relationship and the gender of the dyads affected inter-brain synchrony. Our findings indicate that the way people connect depends on whom they move with and also what type of movements they are engaged in. For example, whether this is moving as one-body with someone from the same gender or whether this is moving while shifting to focus away from your closely related partner.

In conclusion, our findings do suggest there might be a universal way to connect but how or even if this is related to inter-brain synchrony and the subjective experience of social connectedness remains to be seen.

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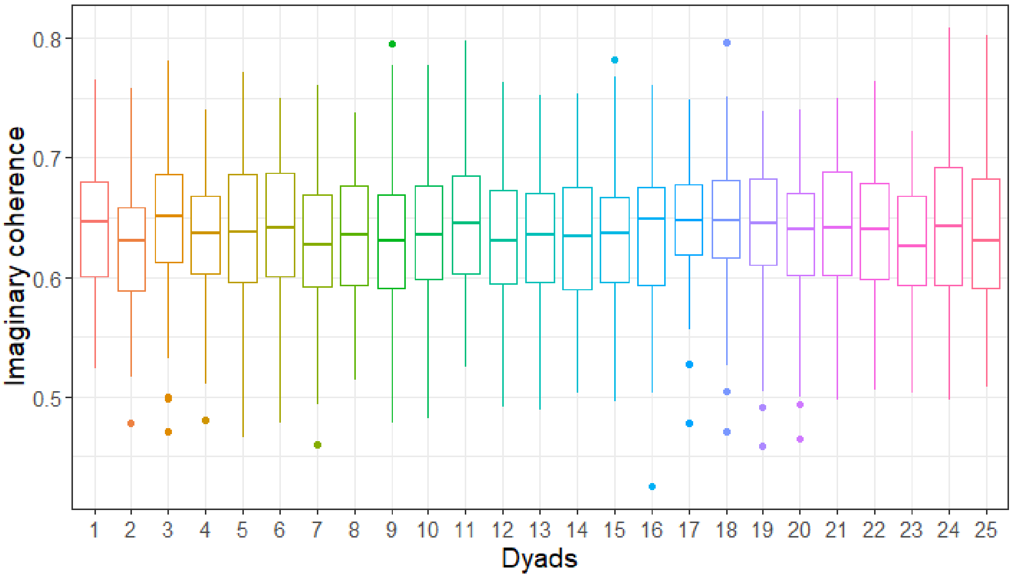
Appendices

A Data combination conditions

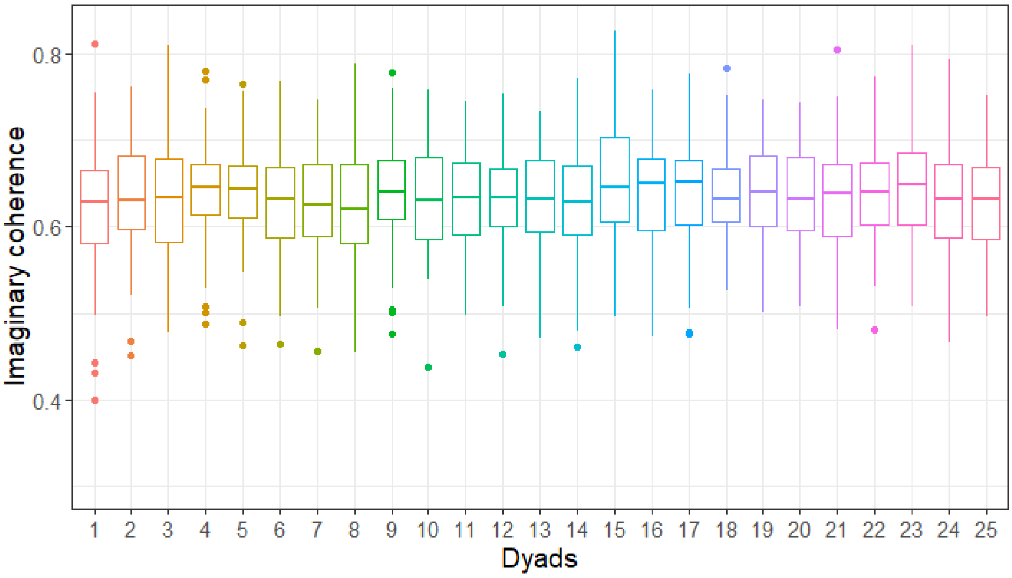
Table 6: The combination of data for the facing and synchronous condition.

	Facing	**Not facing**
Synchronous	Facing synchronous	Not facing synchronous
Asynchronous	Facing asynchronous	Not facing asynchronous

B Imaginary coherence box plot dyads



(a) **Dialogue** (AF3)



(b) **Shift-of-focus** (AF3)

Figure 10: Box plots presenting the variance in the imaginary coherence for the *theta* band for each dyad for the (a) **dialogue** condition and the (b) **shift-of-focus** condition.

C Division dyads contact and relation

Table 7: Division of the various frequencies of contact for the frequent and not frequent contact group.

Frequent	Not frequent
Everyday	3-4 days a week
6 days/week	2-3 days a week
5 days/week	Once a week
At least 4 days a week	Twice a month
	1-2 times/month
	Once a month
	Once in 1-2 months
	Never seen before

Table 8: Division of the various closeness of relation for the close and not close relation group.

Close	Not close
Spouse/couple	Friends
Sisters	Friends 1,5 months
Old friends (4 years)	Classmates/friends
Old friends (2 years)	Colleagues
	Strangers

D Division dyads subjective ratings for mental and physical connection

The facing/not facing and synchronous/asynchronous conditions contain more dyads because it is a combination of conditions. The abbreviations in the following two tables stand for; synchronous (Sync), Shift-of-focus (SoF) and asynchronous (Async).

Table 9: Division of dyads based on the subjective ratings for each condition for mental connection.

	Alone	Dialogue	Facing	Sync	One-body	SoF	Not facing	Async
High average	8%	80%	56%	34%	68%	8%	12%	34%
High difference	4%	20%	34%	30%	32%	40%	18%	22%
Low average	88%	0%	10%	36%	0%	52%	70%	44%

Table 10: Division of dyads based on the subjective ratings for each condition for physical connection.

	Alone	Dialogue	Facing	Sync	One-body	SoF	Not facing	Async
High average	0%	64%	38%	18%	84%	12%	6%	26%
High difference	4%	32%	42%	40%	32%	20%	26%	28%
Low average	96%	4%	20%	42%	0%	68%	68%	46%

E Subjective ratings mental and physical connection for the uncombined condition

For the laboratory experiment the dyads moved in various social and nonsocial conditions. Whether the dyads moved synchronously or asynchronously was combined with the dyads either facing each other or not facing each other. When doing the analysis the data point were combined. For example, for the subjective ratings of the **facing** condition, the subjective ratings of **facing synchronous** was combined with **facing asynchronous**. Figure 11 shows the average subjective ratings for the uncombined **facing** and **synchronous** conditions.

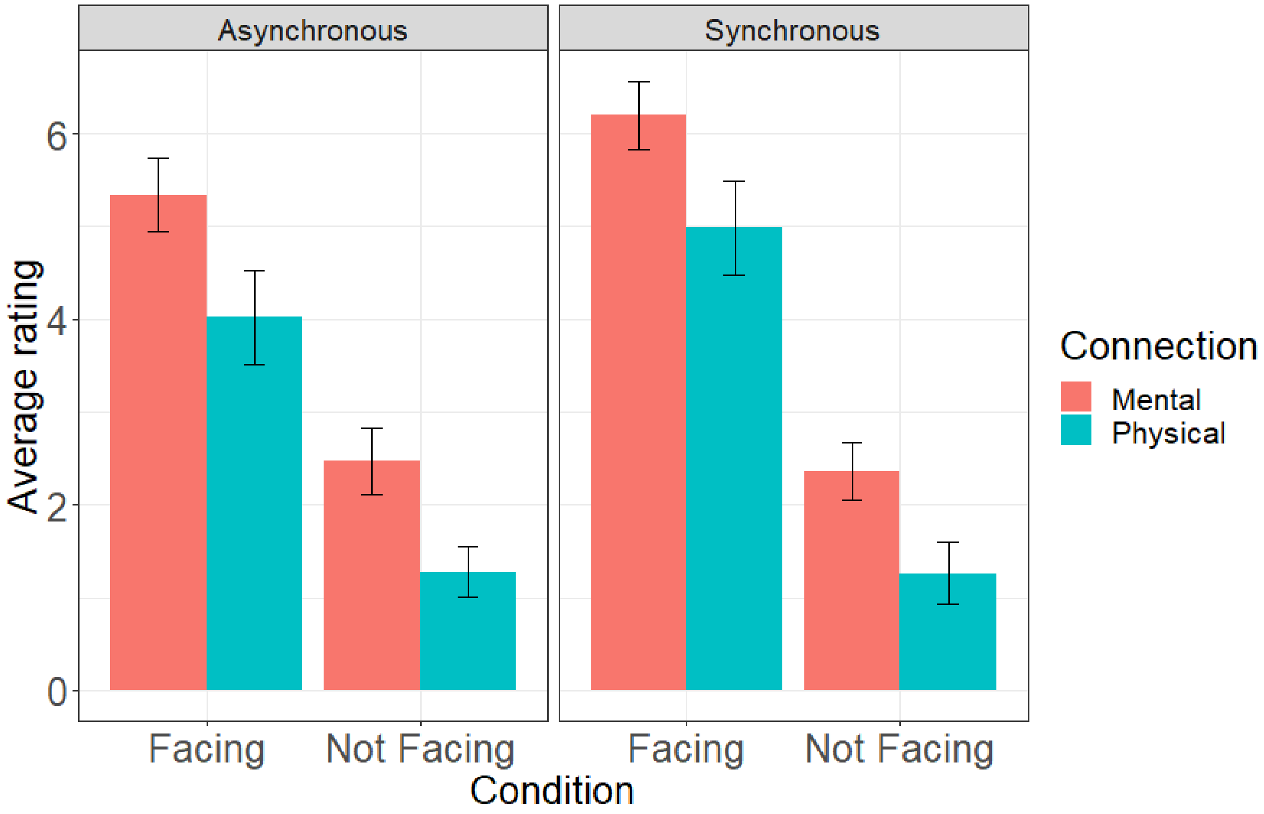


Figure 11: Average subjective ratings, both mental and physical connection, for the separate facing and synchronous conditions.

F Correlation results inter-brain synchrony measures

For investigating the correlation between the mean PLV and the imaginary coherence we ran a repeated measures correlation using R's *rmcorr* package (Bakdash & Marusich, 2017). The repeated measures correlation can deal with non-independence in the data. This method allows to conduct correlation test without aggregating the data which can lead to misleading results (Bakdash & Marusich, 2017). The correlation between the two inter-brain synchrony measures were determined for a selection of the data based on the results of the of the statistical analysis of the laboratory experiment. The results are present in Table 11. There appeared not to be a correlation between the two inter-brain synchrony measures based on the results present in Table 11 below.

Table 11: The results of the repeated measures correlation test for the selection of the data. The selection of the data was based on the results of the laboratory experiment. All of the p-values $>$ 0.05.

Condition	Channel	Frequency	Correlation	Confidence interval
One-body	O1	Theta	$r_{rm}(2224) = -0.025$	95% [-0.067 0.016]
Shift-of-focus	O1	Theta	$r_{rm}(2224) = -0.04$	95% [-0.081 0.002]
One-body	O1	Alpha	$r_{rm}(2224) = -0.019$	95% [-0.061 0.022]
Shift-of-focus	O1	Alpha	$r_{rm}(2224) = -0.025$	95% [-0.067 0.016]
Facing	T8	Alpha	$r_{rm}(4474) = -0.016$	95% [-0.045 0.013]
Not facing	T8	Alpha	$r_{rm}(4474) = -0.002$	95% [-0.031 0.028]
Synchronous	CP1	Alpha	$r_{rm}(4474) = -0.013$	95% [-0.042 0.016]
Asynchronous	CP1	Alpha	$r_{rm}(4474) = -0.021$	95% [-0.05 0.009]

* p <.05; ** p < .01; *** p < .001