Quantifying flow with neural synchronisation

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The correlation between neural synchronisation and teamwork has been researched in multiple studies over the last decade. The Phase Locking Index (PLI) has been the most commonly used technique to quantify this correlation. However, this technique can detect spurious correlations when used unmodified. In this study we studied participants while brainstorming (n=14). Two different types of synchronisation are quantified with modified versions of the PLI. A significant but small effect (p-value = 0.0304, Cohen's d = 0.193) has been found for one of the types of neural synchronisation.

Keywords: neural synchronisation, EEG, hyperscanning, phase locking index, coupled oscillators, teamwork

Introduction

Cooperation is an omnipresent aspect of human life. Impact from the presence or absence of good cooperation is felt daily by nearly everyone. Sometimes this is at a very basic and simple level like participating in traffic or waiting in a queue. Sometimes it is as complex as the coordination of an international project. The effects of cooperation can even be encountered indirectly when for example a powerplant has an accident because of the lack of good teamwork. As history has shown this is a very real possibility (Jang, Kim, Oh, & Lee, 2012). The demand for qualities like cooperation, communication and 'flow' between teams has led to numerous books, workshops and trainers that offer to improve these qualities. However, what actually defines good teamwork is often considered to be a subjective measure. People feel the have a 'good flow' or are 'in sync' with each other, but is this quality something that can be quantified? There are some attempts to objectify the quality of cooperation through psychological models or with pseudoformulas that combine intuitive concepts in a mathematical syntax (Nakamura & Csikszentmihalyi, 2014; Csikszentmihalyi, 2015; Gratton, 2007) but none of these attempts can objectively quantify the quality of teamwork. This isn't necessarily a problem and some people might even prefer a subjective assessment in some contexts. Yet, given the omnipresent nature of the phenomenon and the high impact in certain contexts it is plausible that complementing the subjective assessment with an objective quantification is usefull.

Objective feedback on the quality of teamwork can be expected to reinforce good teamwork in the same way people can benefit from neurofeedback regarding qualities like concentration (Arns, de Ridder, & Strehl, 2009; Arns, Drinkenburg, & Leon Kenemans, 2012; Fingelkurts, Fingelkurts, & Kallio-Tamminen, 2015; Hammond, 2007; Surmeli & Ertem, 2010). In addition to that most teams don't have easy access to an objective third party able to give feedback on the quality of their interaction. Because bias in self-reports is a known tendency (Donaldson & Grant-Vallone, 2002; Van de Mortel et al., 2008) objective feedback could help to correct this bias.

Research on neural synchronisation

The phenomena of coupled oscillation is widespread across physics and biology. Examples are encountered in physics in the interaction between planets or pendulums. In biology synchronisation can be found within an individual, for example in the synchronised pulsing of the pacemaker cells of the heart or the cells of the nervous system that control breathing and digestion (Strogatz & Stewart, 1993). However, synchronisation is not limited to individuals: consider the chirping of crickets, the flashing of fireflies or a flock of birds or fish. The core idea of quantifying teamwork is to establish a correlation between the quality of teamwork and neural synchronisation. Neural synchronisation can be defined as a type of coupled oscillation between two EEG-signals.

To establish neural synchronisation it is necessary to simultaneously scan multiple brains. This technique is called 'hyperscanning' and is done with methods like fMRI of EEG (Sänger, Lindenberger, & Müller, 2011). This research has focused on EEG-signals because of the better time-resolution of EEG as well as the availability of portable, low-cost EEG-devices. The last decade there have been multiple studies that have tested the hypothesis that synchronisation between EEG-signals is correlated with teamwork. A selection of research designs in the past decade that have found significant effects regarding this correlation has been listed by Grouls (2019) and includes the formation of spontaneous leader-follower pairs during group discussion (Shi et al., 2015), joint attention in a visual

Figure 1. Synchronous flashing fireflies. Image Credit: Radim Schreiber

search task (Szymanski et al., 2017), cooperation on a puzzle task (Cha & Lee, 2018), spontaneous synchronisation of hand movements (Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010; Delaherche, Dumas, Nadel, & Chetouani, 2015), the degree of cooperation between pilots in different phases of a flight (Toppi et al., 2016), guitarists engaged in musical improvisation (Müller, Sänger, & Lindenberger, 2013) and guitarists playing melodies together (Lindenberger, Li, Gruber, & Müller, 2009; Sänger, Müller, & Lindenberger, 2012). Most of these studies use the Phase Locking Index (PLI) as a mathematical approach to quantify the effect. The PLI will be discussed in more detail later on in the subsection Phase Locking Index.

Problems with the research design

A critique on some of the research designs is the lack of a proper control condition where the social aspect is missing while all the aspects of perceptual input and motor output are kept constant (Szymanski et al., 2017). After all, it might be a possibility that synchronised hand movements or simultaneously playing the same music have a neural substrate that is interpreted as neural synchronisation. This could lead to false positives when the effects of people performing the same physical activity are mistaken for the social effects of teamwork (Szymanski et al., 2017; Grouls, 2019). This critique is explicitly addressed in the research of Szymanski et al. (2017) by varying joint attention in a visual search task while all other visual and motoric variables were kept constant.

Another problem is the definition of teamwork. Improvising music can be argued to be require a very different type of teamwork as solving a puzzle or making simultaneous hand-movements. This means that the research on neural synchronisation might be a generalisation over completely different phenomena. In addition to that, finding a correlation with teamwork is not the same as finding a correlation between the quality of teamwork.

Hypothesis

This study examines the correlation between teamwork during brainstorming and neural synchronisation. The hypotheses that have been tested in this study are:

(i) The Phase Locking Index, controlled for Phase Stability, is significant higher under the cooperative condition.

(ii) A higher length of the Neural Synchronisation Vector correlates with the phase of the Neural Synchronisation Vector being closer to 0.

(iii) Neural Synchronisation Vectors with a higher length do not follow a uniform distribution for their phase but will be clustered around some constant.

These hypotheses test for different types of neural synchronisation. Hypothesis (i) is able to show Frequency Synchronisation while hypotheses (ii) and (iii) are able to show Phase Synchronisation. The differences between these two types will be explained in the following section.

Phase Locking Index

The most commonly used method to quantify neural synchronisation is the Phase Locking Index. Confusingly, this technique is referred to by different authors as respectively the "Mean Phase Coherence", "Phase Locking Value", "intensity of the first Fourier mode of the Phase Distribution" and "Phase Locking Index" (Boon et al., 2009; Grouls, 2019). This paper will adopt the nomenclature ‘Phase Locking Index’ because it is used by multiple authors (Boon et al., 2009; Sänger et al., 2011, 2012; Chavez, Le Van Quyen, Navarro, Baulac, & Martinerie, 2003; Stam, Nolte, & Daffertshofer, 2007; Lindenberger et al., 2009; Szymanski et al., 2017) and is argued by Boon et al. (2009) to most precisely reflect the nature of the measure.

The EEG-signal is an oscillating composite electrical signal. This signal, measured at the skin of the forehead, is in fact the summation of a large amount of single neurons (Bruch, 1959; Ward, 2003; David & Friston, 2003). The calculation of the PLI starts with decomposing this combined signal into a summation of sinusoids, known as a Fourier series (Sigl & Chamoun, 1994). The discrete Fourier transform is a function $\mathbb{R} \rightarrow \mathbb{R} \times \mathbb{I}$ that maps a real-valued timeseries over some period t to pairs of a frequency f and a complex number c. The complex number c is a compact representation of the sinusoid at frequency f. The original signal can be reconstructed as a summation of all sinusoids. This operation effectively maps every sinusoid to a complex vector on the unit circle which allows for efficient calculations. The phase φ of a signal c at frequency f can be obtained with the following equation (Rosenblum, Pikovsky, Kurths, Schäfer, & Tass, 2001):

$$\varphi \equiv Arg(c) \quad (1)$$

For two signals c_1 and c_2 with a phase of respectively φ_1 and φ_2, the relative phase difference Ψ is calculated as (Rosenblum et al., 2001):

$$\Psi \equiv (n\varphi_1 - m\varphi_2) mod 2\pi \tag{2}$$

The variables n and m can be any integer for the general purpose of calculating the phase locking between coupled oscillators (Rosenblum et al., 2000, 2001) but because only similar frequencies will be compared between both Fourier series in our context it is possible to simply take $n = m = 1$. If the two signals are unsynchronised, the phase differences over a longer period of time will follow a uniform distribution on the unit circle. Any peak in the distribution of Ψ can be understood as an indication of phase synchronisation (Rosenblum et al., 2001; Boon et al., 2009). This distribution can be quantified as the Phase Locking Index (PLI), which is defined as (Boon et al., 2009; Chavez et al., 2003):

$$\gamma \equiv \left| \left\langle e^{i\psi[k]} \right\rangle_k \right| \tag{3}$$

where $k = \{1, \ldots, K\}$ is a discrete time index, K is the total number of samples, $\langle . \rangle_k$ means the time average and i is the complex number $\sqrt{-1}$. When there is a strong synchronisation between the signals, γ will be close to one while it will be close to zero if there is no synchronisation. This effect is obtained by adding the complex vectors and taking their mean value. A uniform distribution of phase angles will thus lead to a vector length close to zero.

Phase Stability and false positives

There are two types of errors to be avoided: false negatives and false positives. False negatives could be caused by factors like synchronisation errors (discussed in section Synchronisation of devices) or other inaccuracies in the measurements caused by noise. It is pointed out by both Burgess (2013) and Grouls (2019) that an unmodified use of PLI could lead to spurious hyper-connections. Burgess (2013) showed this by using the PLI on simulated data and pseudo-pairs of human data. Grouls (2019) points out that a possible source of false positives with the PLI is the occurrence of Phase Stability. This simply means that the signal is expected to be back at its original position after it makes any discrete amount of complete cycles. The Phase Stability of a signal c is defined mathematically as (Grouls, 2019):

$$\Phi \equiv \varphi_c(t_i) - \varphi_c(t_{i+1}) \tag{4}$$

where $\varphi_c(t)$ is the phase of a signal c with frequency f at time t. The index i indicates a time in seconds at which the signal is measured. If it holds that $i = 0$ is equal to the start time of the signal and $\forall i \in I(I \subseteq \{1/f, \ldots, K/f\})$ where $\{1, \ldots, K\} \in \mathbb{N}$ and K/f is the end time of the signal, then it will always be the case that a stable frequency has made one or more full cycles and thus has to be back at its original position. The difference between the phases will approach 0 if there is Phase Stability. This implies that the distribution of Φ is expected to have a mean of 0 with a very small variance in the case of a high Phase Stability but will approach a uniform distribution in the case of a complete absence of Phase Stability.

It is important to note that the definition of Phase Stability of a signal is completely independent from the Phase Stability of another signal. For two arbitrary signals c_1 and c_2 at the same frequency f it can be proven logically that the presence of Phase Stability will lead to a high value of the PLI, even in the complete absence of synchronisation between the two signals (Grouls, 2019). The only thing needed is an alternative cause for the signals to gain more Phase Stability in the experimental condition. If anything in the research design would cause the EEG of participants to gain more Phase Stability as compared to the control condition, this would cause the PLI to increase even in the absence of synchronisation between the individuals. This obviously is a false positive because Phase Stability would be mistaken for neural synchronisation. This is the reason the PLI will exclusively be accepted as a significant indication for neural synchronisation if changes in Phase Stability are ruled out as a possible alternative cause.

Frequency synchronisation. The PLI, even when controlled for Phase Stability, does not make any distinction between the the amount of difference between the phases. As long as Ψ is stable at an arbitrary value, γ will reflect this in a higher value. This means that a significant increase in γ that cannot be explained by changes in Phase Stability indicates that there is more overlap between the stable frequencies of two individuals when they cooperate. This type of synchronisation can be defined as Frequency Synchronisation. This type of synchronisation does not imply that the phases of these frequencies are synchronised aswell.

Neural Synchronisation Vector

Phase synchronisation. Some research speaks explicitly about 'phase synchronisation' and 'suggest that phase synchronisation constitutes a neural correlate of social facilitation' (Szymanski et al., 2017). This can be interpreted as a synchronisation at the phase level, in the same way two people would synchronise the hands of a clock. Phase synchronisation is a stronger type of synchronisation than frequency synchronisation. This requires a lot more exchange of information than is the case with frequency synchronisation. It would imply that brains have a mechanism to synchronise the phase of similar frequencies at a millisecond level. The difference between the two types of synchronisation could be explained with the metaphor of a choir. In the case of frequency synchronisation without phase synchronisation two choirs are able to sing a song at the same speed but they do not know if the other choir has just started or is somewhere halfway the song. In the case of both frequency synchronisation and phase synchronisation two choirs sing a song at the same speed and in addition to that they have information about when the other choir started singing and at which point in the song they are. This last condition means they will be able to sing simultaneously, or in canon.

To measure this type of synchronisation the Neural Synchronisation Vector can be used (Grouls, 2019):

$$\vec{\gamma} \equiv \left\langle e^{i\psi[k]} \right\rangle_k \quad (5)$$

The length of $\vec{\gamma}$ is similar to γ and can indicate Frequency Synchronisation when controlled for Phase Stability. The phases of $\vec{\gamma}$ will have an uniform distribution if there is no Phase Synchronisation. If there is Phase Synchronisation, the distribution of the phases of $\vec{\gamma}$ will cluster around some constant value for higher lengths.

Methods and procedure

Research Design

To test the hypotheses a randomized within-subjects design was used to measure synchronization between participants while brainstorming both individually and in pairs. Initially participants were told the goal of the experiment and what they could expect to happen during the different phases of the experiment. Once participants agreed to this, they were asked to sign an informed consent, stating that they agreed to the anonymized recording of their EEG-signal and some additional information such as their age and gender. Once this was done participants were guided to the location where the experiment would be performed. The experiment was randomized in both the brainstorm prompts and the starting condition. This was done in order to counterbalance effects from the differences between the brainstorm prompts or effects where the second experimental condition would be influenced by the first.

The first phase consisted randomly of either the individual control condition in which both participants had their own room during the brainstorming or the experimental group condition in which both participants were in the same room and had to cooperate during the brainstorm. Participants were asked to wear a Muse headband. They were shown the sensitivity of the device for physical movements and asked to move as little as possible during the experiment.

Participants were then given the brainstorm prompts that consisted of two different words. They were instructed to find as many similarities as possible between the two words. In the control condition participants did this individually while sharing their ideas with the research assistant. During the experimental situation participants searched for similarities and shared these with each other. Before the start of the experimental condition they were encouraged to help and inspire eachother to find as many similarities as possible. During the whole experiment participants wore the Muse headband.

Every condition was separated into three phases. The participants would talk out loud during the first phase of the experiment that took 180 seconds. The participants would then be told to be silent while continuing to brainstorm during the second phase, which took 60 seconds. Finally they would be asked for another 60 seconds to share the result of their silent brainstorm in the third phase. This would bring the total duration to 5 minutes for every condition. The first phase of the experiment was intended give the participants some time cooperate and possibly attain some form of neural synchronisation. The second phase was intended to minimise the disturbance of the signal caused by talking. This is the part of the data that was actually used in the analysis. The third phase was intended as a motivation for people to continue brainstorming during the second phase.

Participants & location

Participants were recruited at several locations of Utrecht University. Specifically use was made of silent rooms in the Koningsberger building of Utrecht Science Park and Drift 21 in the inner city. As such participants were mainly students. No monetary reward was given. Participants were not restricted to a single nationality or language as long as both participants spoke the same languages.

Choice of brainstorming prompts

To ensure similar conditions between all participants, prompts were needed that would minimize the chance of causing a distracting emotional response in participants. As such, the decision was made to select simple and neutral objects. The first brainstorm prompt was the set of words 'giraffe' and 'guitar'. The second prompt was the set of words 'tower' and 'water'. These subjects were deemed sufficiently neutral for the task as hand while both sets roughly have a comparable difficulty level with regards to finding similarities.

Materials

The Muse 2 headband was used to measure the EEG-signal of the participants (Muse, 2019). The Muse is a portable EEG-device from the Canadian company InteraXon and is designed to give neurofeedback during meditation. Advantages of this device are the portability, the relative low price when compared to other EEG-equipment and the sufficient reliability to do research (Krigolson, Williams, Norton, Hassall, & Colino, 2017). The Muse measures brain-activity at four locations: two frontal locations (AF7 and

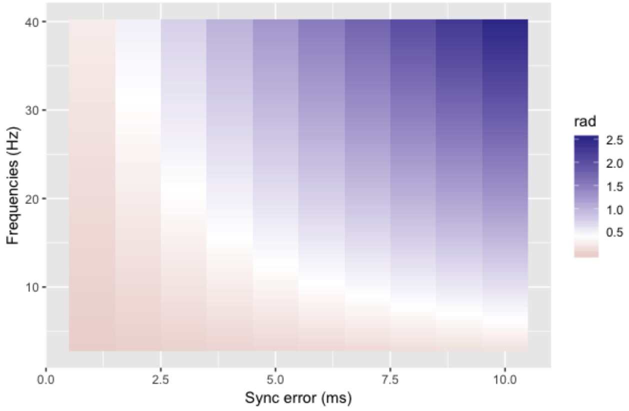

Figure 2. Synchronisation error

AF8) and two temporal locations (TP9 and TP10). The headbands were connected to laptops of the research assistants through BLED112 low energy Bluetooth dongles. The software package muselsl (Barachant, 2019) was used to record the raw EEG-signals.

Synchronisation of devices

One of the technical problems encountered was the issue of synchronization between EEG-measurements. As mentioned before these errors could lead to false negatives for the NSV. Because the PLI ignores shifts in the relative phase by a constant, these possible synchronisation errors would not cause false negatives for the PLI.

In an ideal situation, both headbands would be connected to the same computer in order to ensure similar timestamps on the EEG-signals. However, connecting multiple devices to the same computer was found to be no longer possible with the current combination of hardware and all of the available software packages. Making the connection of multiple devices to a single laptop possible would involve rewriting the muselsl code handling the Bluetooth connections, while accounting for different drivers and operating systems. For this reason, the decision was made to connect the headbands to different computers while synchronising the clocks of both computers with an external server[1]. This server was selected from one of four available servers by comparing the ping times and choosing the server with the lowest mean ping time. 900 pings were executed during the period the experiments were conducted.

An overall median ping time of 6.36ms was found, and a mean of 8.11ms. Of all pings, 97.5% was below 15.9 ms. However, the pings did not follow a normal distribution and were split into two different groups to be able to draw conclusions. The first group consists of ping times below 15.9 ms and covers 97.5% of the ping times. This group has a standard deviation between 0.95 ms and 1.46 ms, depending on the location and time of the day. The second group consists of ping times above 15.9 ms and covers 2.5% of the ping times. This group has a mean ping time fluctuating between 32.7 ms and 122 ms depending on location and time of the day. These statistics suggest a 97.5% chance of encountering a very low ping time with a small variance and a 2.5% chance of encountering an extreme delay in ping times with a very high variance. Both computerclocks were synchronised at the beginning of every day of conducting experiments. Thus, every day had a 95.06% chance of not encountering a delay while synchronising one of the computerclocks. In this case the 95% interval of the difference between two ping times would be an interval of 4 standard deviations which is equal to values between 5.84 ms and 3.80 ms depending on the location and time of the day. Synchronising the clocks on 4 different days lowered the chance of not encountering a delay to 81%.

Even these small errors can cause false negatives and have serious consequences for determining the phase difference between signals, as illustrated in figure 2. The midpoint of the fill color is set to white at $\pi/8$, which translates to a quarter of a complete phase at every given frequency. The impact of the synchronization error varies with the frequency. For a frequency of 8 Hz with a duration of 125 ms for every cycle an error of 3 ms would translate into a phase difference of 0.15 rad for waves that were in reality exactly synchronized. This equals to an error of 2.4%. While this seems acceptable, a frequency of 40 Hz with an 5 ms error would lead to a difference of 1.5 rad, which is enough to make significant conclusions at the level of phase synchronisation impossible. In the case a delay was encountered during one of the synchronisations, all measurements regarding the phase would have been useless during that day.

Results

Collected data

9 experiments with 18 participants have been conducted. Of these, 2 experiments were excluded because the Bluetooth connection failed during phase 2 at one of the computers. This brings the amount of participants down to 14. The mean age of the participants in the resulting experiments was 22, while 64% was male. One of the couples were native English speakers. 3 out of 7 experiments started in the group condition, the other 4 in the individual condition. The second phase of the experiment was used exclusively for the calculations and segments were created with a duration of 1 sec to calculate the Fourier series. Only frequencies between 3 and 40 Hz were used in discrete steps of 1 Hz.

Frequency Synchronisation

The PLI has been used to find evidence of Frequency Synchronisation at one of the four locations. PLI was calculated

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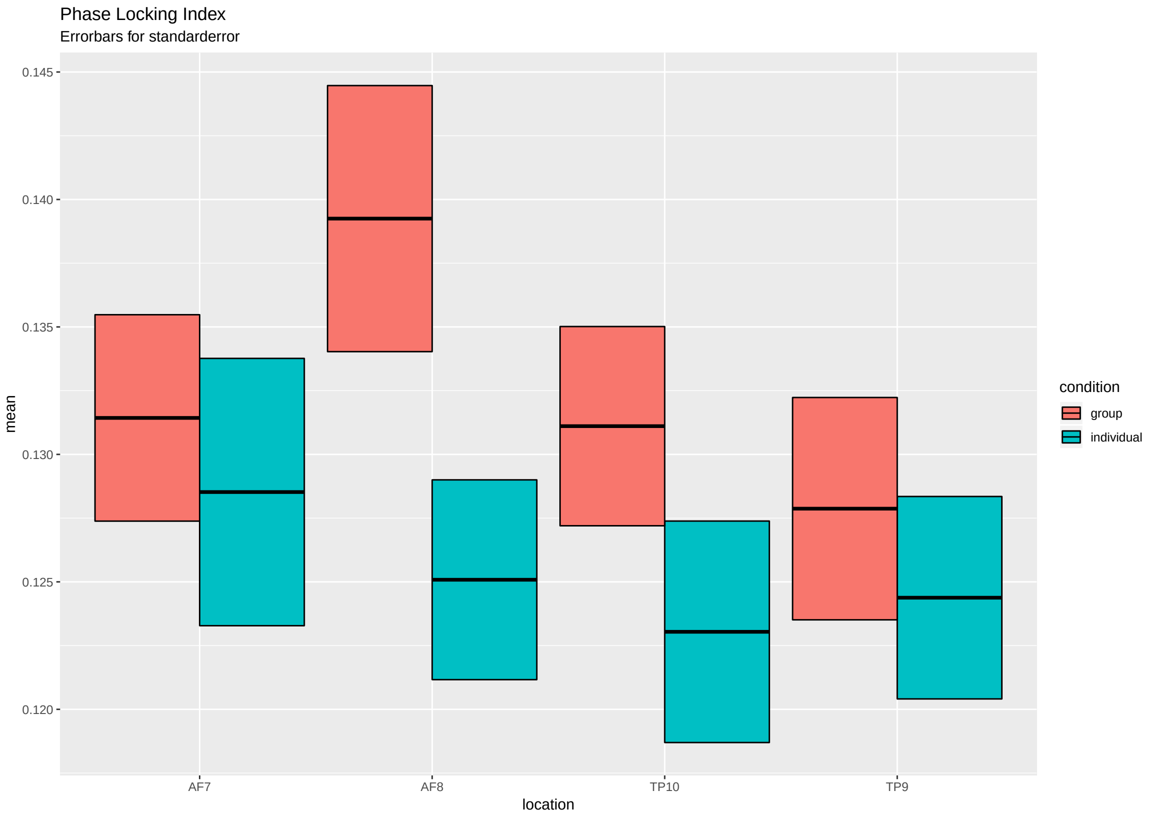

Figure 3. Mean Phase Locking Index

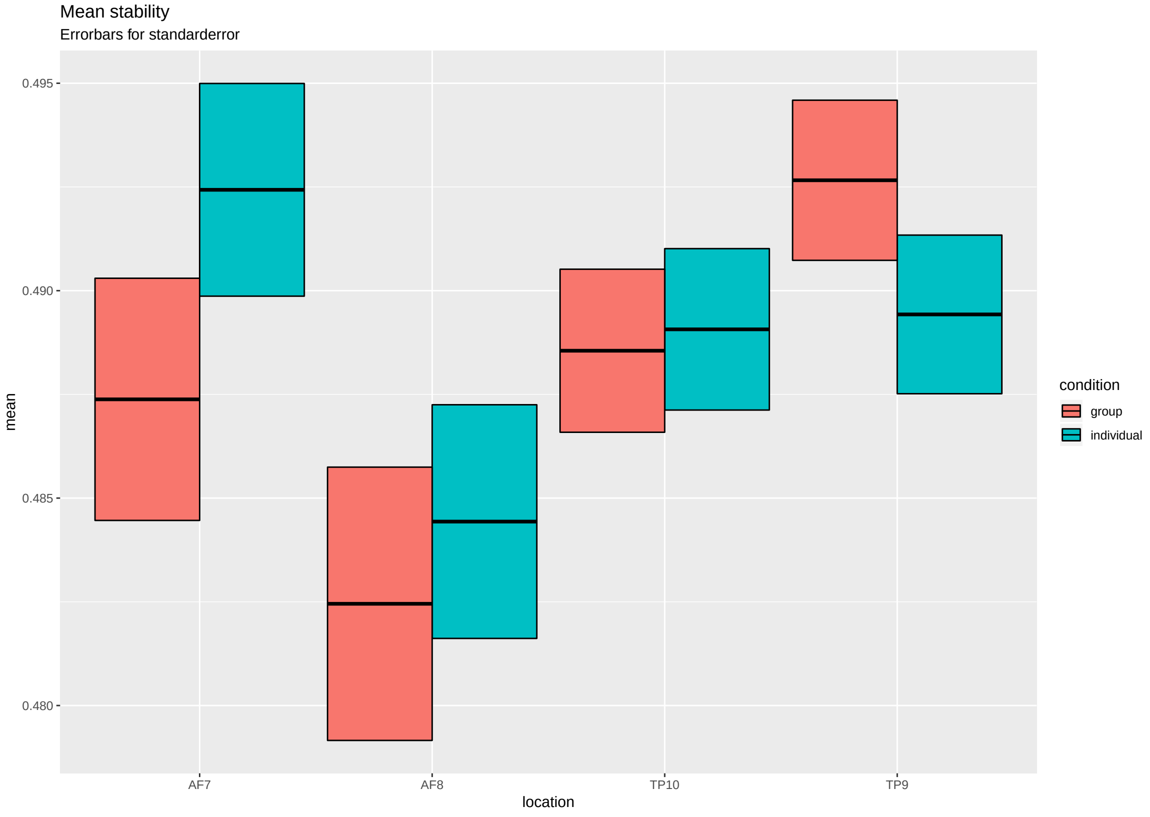

Figure 4. Normalised mean Phase Stability

location	condition	n	mean	se	d
AF7	group	252	0.131	0.004	0.039
AF7	individual	252	0.129	0.005	0.039
AF8	group	252	0.139	0.005	0.193
AF8	individual	252	0.125	0.004	0.193
TP10	group	252	0.131	0.004	0.123
TP10	individual	252	0.123	0.004	0.123
TP9	group	252	0.128	0.004	0.053
TP9	individual	252	0.124	0.004	0.053

Table 1
Mean PLI

condition	location	n	mean	se
group	AF7	252	0.487	0.003
individual	AF7	252	0.492	0.003
group	AF8	252	0.482	0.003
individual	AF8	252	0.484	0.003
group	TP10	252	0.489	0.002
individual	TP10	252	0.489	0.002
group	TP9	252	0.493	0.002
individual	TP9	252	0.489	0.002

Table 2
Normalised mean Phase Stability

condition	location	n	r
group	AF7	252	-0.127
individual	AF7	252	0.089
group	AF8	252	-0.010
individual	AF8	252	-0.080
group	TP10	252	-0.021
individual	TP10	252	0.042
group	TP9	252	0.061
individual	TP9	252	0.019

Table 3
NSV correlation phase~length

for every pair of participants at every frequency between 3 Hz and 40 Hz. Figure 3 and table 1 show the mean and the standard error of the PLI. They show a small but significant (Welch Two Sample t-test: df = 465.75, p-value = 0.0304, t = 2.17) effect at the frontal AF8-location. A Cohen's d of almost 0.2 can be interpreted as a small effectsize.

If the PLI is differentiated for every location, condition and duo as illustrated in figure 5 it is clear that there are occasions were the PLI is higher in the individual condition. It is even the case that the maximum PLI is found in the individual condition with a PLI of 0.88 at 21 Hz for pair 3 at location AF7. This is an example of a the impact of Phase Stability that occurs at similar frequencies by coincidence. While coincidences like these are expected it is important to rule out Phase Stability as an alternative cause for the higher PLI.

Could the effect that is seen at AF8 be caused by increased Phase Stability in the group condition? The mean Phase Stability for every condition and location is shown in figure 4 and table 2. The Phase Stability is normalised according to the following equation:

$$\Phi_{norm} \equiv \begin{cases} 1 - \frac{\Phi}{\pi} & \text{if } 0 < \Phi \leq \pi \\ 1 + \frac{\Phi - 2\pi}{\pi} & \text{if } \pi < \Phi < 2\pi \end{cases} \quad (6)$$

This way the values are normalised to a range between 0 and 1 and inverted. A value of 1 equals to a maximum stability and a value of 0 equals to a minimum stability. If the increased PLI at location AF8 is a false positive caused by increased Phase Stability, there would have been a higher mean Phase Stability in the group condition at AF8. The opposite is the case: there is actually an overall lowered Phase Stability at location AF8, so the higher value of the PLI can not be attributed to a higher Phase Stability.

Phase synchronisation

If Phase Synchronisation would have occurred the data would need to show a correlation between the length of the NSV and the phase of the NSV. The phase of the NSV is normalised with the use of equation (6). The values range between 0 and 1, such that 1 equals no phase difference and 0 is equal to a maximum phase difference of π rad. This way a positive correlation indicates Phase Synchronisation. As can be seen in table 3 the Pearson's r does not show any effect at all.

However, it could still be the case that there are other values around which higher lengths of the NSV are clustered. After all, any deviation of a normal distribution could indicate some form of phase synchronisation. If the mean values of the NSV vectorlength are binned over ranges of the NSV phases, possible clusters could show up. As a binsize, 1/7th of a full phase was chosen in order to keep minimum amount of datapoints in every bin reasonable (yielding to a minimum of 25 datapoints for this binsize). Furthermore, the expected impact of the synchronisation error as shown in figure 2 was considered when picking this binsize. Figure 6 shows boxplots of the mean vectorlengths for every bin. From this it is clear that there is no significant deviation from an uniform distribution.

Conclusion and discussion

From the statistical analysis it is clear that hypotheses (ii) and (iii) are not supported by the data. The conclusion that can be made is that there is no evidence for Phase Synchronisation with this experimental setup. It cannot be ruled out that this is a false negative, due to the synchronisation error in the setup. After all, an 80% chance of not encountering a delay is substantial. And even variations close to the expected

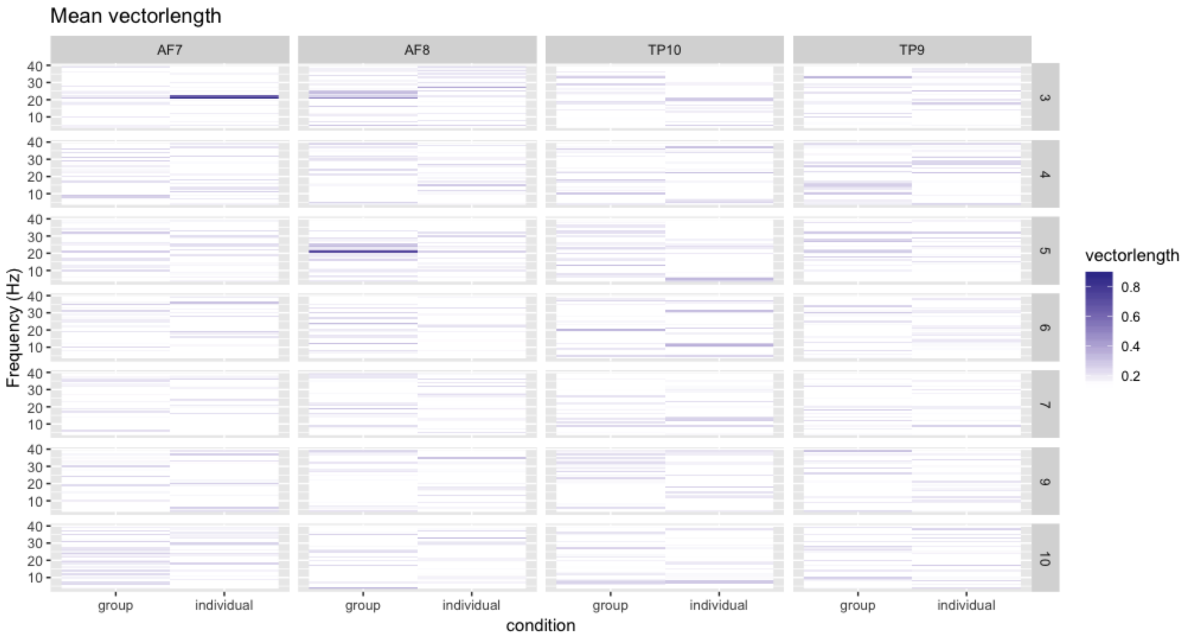

Figure 5. Differentiated Phase Locking Index

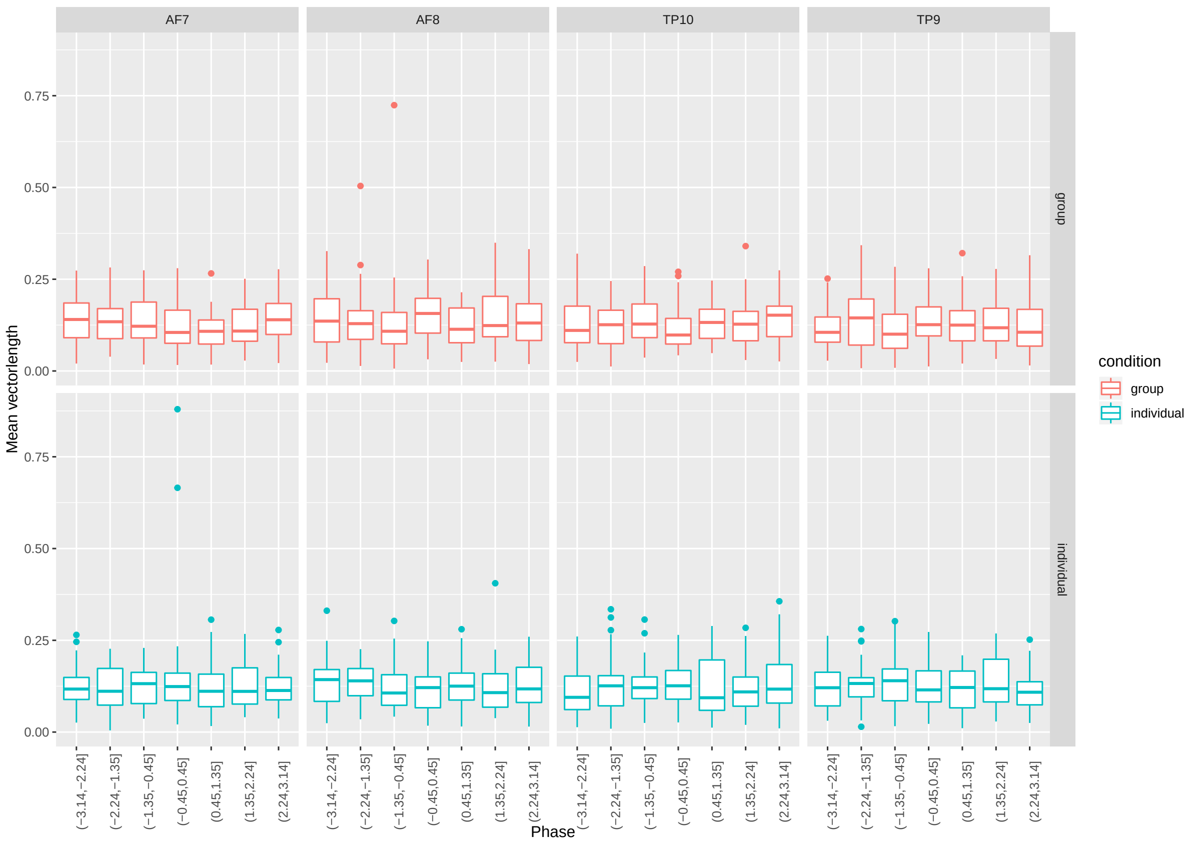

Figure 6. Binned mean vectorlength

synchronisation error of 5 ms can have a serious impact on the distribution for the higher frequencies, especially if the synchronisation varies across the days the experiments were performed. Future research could take precautions to avoid these false negatives by lowering the synchronisation error below 1 ms for example by finding a way to connect two EEG-devices to the same computer.

Hypothesis (i) is supported by the data, even though the effectsize is small. A low Cohen's d is often indicative for a small dataset. Extending the amount of participants might possibly increase the effectsize. A possible critique on the experimental design is that the cooperation takes place during the first phase of the experiment, while only the second phase of the experiment could be used because of the noise produced by the talking during the first phase. This could have lowered the neural synchronisation induced by the first phase.

Interpretations of Frequency Synchronisation

The correlation between the PLI and teamwork seems to be a significant effect that has been replicated by a variety of research during the last decade. However, it is still unclear if the PLI correlates with the quality of the teamwork and how exactly a higher Frequency Synchronisation should be interpreted. For example, it could be the case that Frequency Synchronisation is increased in cases where people feel threatened by others in an attempt to better predict possible aggressive behavior. That would mean that higher Frequency Synchronisation would indicate fear instead of better cooperation or even 'flow'. Other experimental designs could shed more light on how to interpret Frequency Synchronisation. Dynamic neurofeedback could also be an interesting option to explore, because participants would be able to give a subjective report of how it feels to have an increased Frequency Synchronisation.

Ethical considerations

The concepts of cooperation and flow as considered in this research are inextricably linked to many processes in society. As such some additional ethical considerations are made in addition to the usual data protection and informed consent. Firstly, when working with these concepts care must be taken to realize that their subjective experience might very well be culturally bound. As such results from one experiment cannot be directly extrapolated to persons of other cultures. Secondly, even within one culture there might be minorities who experience flow differently or whose brain activity might not match that of the majority. In persons with a non-usual brain anatomy such as those with Autism Spectrum Disorder (Paakki et al., 2010) or similar conditions flow might manifest differently in the EEG. Finally, even if the research extrapolates perfectly to all participants and is able to quantify the quality of teamwork there are cases where this might have negative consequences for participants or society as a whole. Consider as an extreme example attempts to measure dissent EEG-patterns in a dictatorial society. Any application using the results of this or similar experiment should be built with these three points in mind.

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