Intersubject EEG Coherence in Healthy Dyads During Individual and Joint Mindful Breathing Exercise: An EEG-Based Experimental Hyperscanning Study

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ABSTRACT

Intersubject electroencephalogram (EEG) coherence of 11 couples was measured during an individual and joint practice of a guided mindful breathing exercise. Additionally, the relationship of personality dimensions of agreeableness and extraversion with intersubject coherence was examined. There were four male-male pairs, five female-female pairs, and two male-female pairs. The age of the participants ranged between 18 and 28 (M = 22.3, SD = 2.9). During the counterbalanced joint and individual conditions, the same mindfulness listening tape (3 min) was played, while during the individual task, a screen was placed between the two participants. Results showed an increase in intersubject coherence during joint practice compared to individual practice in frontal (F8) and temporal (T5 and T6) electrodes in the alpha band. With respect to personality characteristics, higher agreeableness of a dyad was associated with an increase in intersubject coherence in in temporal (T6) theta band. The increase in intersubject coherence in the theta band in high agreeableness subjects during joint practice might be associated with theory of mind activation. This study provides new insights concerning brain coherence in healthy people during joint mindful breathing, including the association with personality characteristics.

KEYWORDS
EEG,
hyperscanning,
inter-subject EEG coherence,
mindfulness,
agreeableness,
extraversion

INTRODUCTION

Humans are social creatures with a natural desire for social interaction (Baumeister & Leary, 1995). When two individuals interact, they become a coupled unit by continuously and mutually adapting their own actions to those of their partner. In the past, research on social cognition has focused mainly on single individuals in passive social contexts, such as observing pictures of social or emotional stimuli on a computer screen. However, this approach has shortcomings, with the most obvious one being that these passive social contexts do not take into account how social cognition is regulated during live, dynamic interactions with actual people. To solve this problem, Duane and Behrendt (1965) introduced the concept of measuring several subjects simultaneously using electroencephalography (EEG) to assess their common brain activities during social interactions. Although their idea of simultaneous multisubject scanning was quickly forgotten, it was revived by Montague et al in 2002 and renamed hyperscanning..

Hyperscanning has been performed using various neuroimaging techniques, including EEG (Astolfi, Toppi, De Vico Fallani, et al., 2011; Astolfi et al., 2010; Babiloni, Astolfi, et al., 2007; Babiloni, Cincotti, et al., 2007; Babiloni et al., 2006; De Vico Fallani et al., 2010; Dumas et al., 2010; Labooy-Speksnijder et al., 2018; Lindenberger et al., 2009; Sanger

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et al., 2012, 2013; Szymanski et al., 2017; Tognoli et al., 2007). For example, in an EEG hyperscanning study, brain oscillations were found to synchronize between listeners and speakers interacting through speech (Pérez et al., 2017).

Other hyperscanning studies used functional magnetic resonance imaging (fMRI, Fair et al., 2007; King-Casas et al., 2005; Krill & Platek, 2012; Montague et al., 2002; Saito et al., 2010; Tanabe et al., 2012) and functional near-infrared spectroscopy (fNIRS, Cui et al., 2012; Funane et al., 2011; Holper et al., 2012; Jiang et al., 2012; Liu et al., 2016). In one study using fNIRS, the synchronization of specialized, across-brain, neural processors during eye-to-eye contact between dyads was examined. Results revealed a left frontal, temporal, and parietal long-range network mediating neural responses during eye-to-eye contact, providing insight into mechanisms of social and interpersonal interactions (Hirsch et al., 2017). In another study, prefrontal neural activity was measured in parents and children with fNIRS hyperscanning. Results indicated that during cooperation, the parents' and children's brain activities synchronized in the dorsolateral prefrontal and frontopolar cortex, whereas no brain-to-brain synchrony was observed during parent-child competition, stranger-child cooperation, and stranger-child competition (Reindl et al., 2018).

Although EEG has a limited ability to localize deeper brain structures, it has the advantage of a high temporal resolution, which makes it possible to capture social dynamics at the temporal scale in which they occur (Scholkmann et al., 2013). A significant novelty of the hyperscanning two-brain approach (Konvalinka & Roepstorff, 2012) is that the neural markers of any form of interpersonal interaction can be measured in both brains at the same time (Dumas, 2011). Consequently, the degree of similarity in EEG dynamics of two interacting individuals can be measured, which can be referred to as intersubject brain coherence. These interindividual connections appear to be correlated with successful interactions and may therefore be crucial for identifying the mechanisms underlying continuous and dynamic social interactions. It is thought that these synchronized neural patterns reflect not only similarities in perceptual input or motor output, but also the synchronization of core aspects of social cognition. For instance, in one study, simultaneous EEG brain activity from a class of high school students during regular classroom activities was recorded by portable EEG devices. Student class engagement as well as social dynamics appeared to be associated with the extent to which brain activity was synchronized across students (Dikker et al., 2017).

Thus, the sustained presence of an increase in intersubject coherence during social cooperative tasks compared to either social competitive tasks or individual tasks suggests that in both interacting individuals, there is a specific cognitive process necessary for social (cooperative) behavior. These social aspects include the ability to attribute mental states to partner(s), to predict the behavior motives of partner(s) and to adapt behavior to that of the partner(s.) These abilities are often referred to as theory of mind (ToM, Baron-Cohen, 1995; Schurz et al., 2014). Many previous hyperscanning studies have taken advantage of social cooperative tasks, as cooperation typically involves activating ToM based on the shared goals to which participants are committed (Decety & Sommerville, 2003). During social cooperative tasks – compared to control tasks such as an obstructive task or defective task – increases in intersubject coherence have consistently been observed in prefrontal cortices (PFC), temporal and parietal regions, in the alpha and theta frequency bands (Astolfi, Toppi, Borghini, et al., 2011; Astolfi, Toppi, De Vico Fallani, et al., 2011; Babiloni, Astolfi, et al., 2007; Kawasaki et al., 2013; Lindenberger et al., 2009; Liu et al., 2016; Muller et al., 2013; Toppi et al., 2016). Thus, increases in intersubject coherence in frontal, temporal, and parietal regions in alpha and theta bands that are seen during social cooperative tasks can partly be attributed to increased involvement of ToM.

For example, Kawasaki et al. (2013) performed an EEG study in which dyads carried out a turn-taking speech task by alternately pronouncing letters of the alphabet. As a control, the dyads performed the same alternating speech task, but with a machine. They found an increase in intersubject coherence during the turn-taking task in theta and alpha frequency bands, in temporal and parietal lateral brain regions (Kawasaki et al., 2013). A recent meta-analysis showed that upon ToM activation, a specific brain network becomes active, including the medial PFC and the temporal-parietal junction (TPJ, Schurz et al., 2014). Since ToM is also closely related to cognitive empathy (Grezes & Decety, 2001; Hein & Singer, 2008), the anterior cingulate cortex (ACC) and limbic areas (Hein & Singer, 2008) may also be important during social interactions.

An increasingly popular meditation technique to improve physical and mental health and to relieve stress is mindfulness. Previous studies have shown that mindfulness plays a role in ToM and that mindfulness may even improve ToM (Tan et al., 2014). Mindfulness has been integrated into several clinical intervention programmes, often summarized as mindfulness-based therapies (MBT). MBT is usually given in group form as mindfulness practitioners argue that group mindfulness makes participants more connected to others, creating a sense of harmony. In experienced mindfulness practitioners, increases in frontal midline alpha and theta power have been observed, which reflects ACC and medial PFC activity (Asada et al., 1999; Cahn & Polich, 2006; Chiesa & Serretti, 2010; Ishii et al., 1999). In another study, experienced mindfulness practitioners showed increased alpha power in posterior regions and increased theta power in frontal and temporal-central regions compared to a rest condition (Lagopoulos et al., 2009).

However, an increase in alpha activity does not necessarily reflect mindfulness, but may also reflect relaxation, mind-wandering, or a resting state with closed eyes (Aftanas & Golocheikine, 2001; Morse et al., 1977), especially during self-absorption, as suggested by a study on joint musical action and alpha oscillations (Novembre et al., 2016). In this study, pairs of pianists performed short musical items while behavioral synchronization was manipulated. High behavioral synchronization was associated with a decrease and low behavioral synchronization with an increase of alpha power in right centro-parietal regions. These findings suggest that merely a lower level of behavioural interaction is associated with increase in alpha power. The above evidence suggests that an increase in theta, rather than alpha, in ACC and medial PFC areas should be used as a biomarker for the meditative state (Aftanas & Golocheikine, 2001; Dunn et al., 1999).

Social interactions are influenced by the way people experience and behave in certain situations (Cloninger & Svrakic, 2016). Therefore, the personality of the interacting individuals may also be of interest while studying social interaction. For instance, the personality dimension of extraversion has proved to be a credible predictor of occupations that involve social interaction (Barrick & Mount, 1991). Moreover, both the personality dimensions of extraversion and agreeableness have been shown to be the best predictable dimensions of childhood peer relationship outcomes, including friendship and peer acceptance (Jensen-Campbell et al., 2002), while the personality dimension of neuroticism has a negative impact on the quality of relationships (Donnellan et al., 2005). Notably, agreeableness has been found to be correlated with social-cognitive ToM performance and agreeable individuals exhibit more social reactivity (Adadu et al., 2012) as they seem to be more perceptive to the mental states of others (Nettle & Liddle, 2008). In a study on social reactivity (Knyazev et al., 2019), the association between emotional stimuli (e.g., angry, neutral, or happy faces) and behavioral response was mediated by event-related theta activity in the right temporo-parietal junction. As the strength of the mediation was associated with agreeableness, brain mechanisms underlying reactive social behaviour appear more active in agreeable individuals. In an earlier study (Roslan et al., 2017), higher activation in the right lateral prefrontal cortex in response to fearful faces was found in individuals scoring higher on agreeableness. With respect to extraversion, no consistent results have been found concerning the relation between extraversion and EEG spectral power or event-related potentials (ERPs).

A study by Cuperman and Ickes (2009) showed that similarity in personality traits resulted in good initial social interactions when couples consisted of two extraverts or two introverts compared to conflicting couples consisting of one extravert and one introvert. On the other hand, similar personalities resulted in poor initial social interactions when couples consisted of two disagreeable people.

The primary aim of the present study was to assess intersubject coherence during dyadic mindfulness. We compared the inter-subject coherence during this dyadic task to a well-considered, matched control task in which merely the social interaction was missing. For the joint mindfulness task, participants were seated in the same room, face-to-face to create the feeling of meditating together, while during the control mindfulness task, a screen was placed between the participants in order to generate the feeling of meditating alone. Thus, during joint mindfulness, subjects were aware of each other practicing mindfulness at the same time. As indicated above, practicing mindfulness increases temporal and frontal alpha and/or theta power, while social cooperation has been found to increase intersubject coherence in alpha and theta band in the same regions. Therefore, we hypothesized that this perceived interaction would result in an increase in intersubject coherence of theta and alpha frequencies in frontal and temporal brain regions during the joint mindfulness task compared to the individual mindfulness task.

Finally, we investigated whether dyads with higher average agreeableness or extraversion show a larger increase in intersubject coherence during the joint mindfulness task. Based on the results of the above-cited studies (Haas et al., 2007; Knyazev et al., 2019), we expected increased theta band coherence in right prefrontal or temporal areas in higher agreeableness dyads. As no consistent relations between extraversion and EEG have been reported (Roslan et al., 2017), we could not predict relations between extraversion and intersubject coherence in specific brain regions.

MATERIALS AND METHODS

Participants

A total of 26 healthy volunteers were recruited via a student database, forming 13 nonoverlapping pairs: four male-male pairs, five female-female pairs, and four male-female pairs. Two male-female pairs had to be excluded from all further analyses due to technical problems during EEG recording, leaving a total of 11 pairs for the analyses. The age of the participants included in the analyses ranged between 18 and 28 (M = 22.3, SD = 2.9). All pairs were acquaintances with the length of friendship in years ranging between 1 and 14 (M = 3.82, SD = 3.87). None of the participants had (a history of) psychiatric disorders. Written informed consent was given prior to participation in this study. This study was carried out in accordance with the ethical regulations of the Vrije Universiteit Amsterdam and with a positive advice of the Scientific and Ethical Review Board.

Materials

The mindfulness listening tape (3 min) contained a Dutch woman's voice in which she instructs the listeners to focus on the breathing, to be aware of the present moment and to acknowledge any feelings, thoughts or bodily sensations. The tape also contained two 40-second stretches of silence, during which participants were instructed to continue focusing on the breathing.

The HEXACO Personality Inventory Revised (HEXACO-PI-R) was used to measure participants' personality traits (de Vries et al., 2008). The 104 items included in this survey are designed to measure six personality traits including honesty-humility, emotionality, extraversion, agreeableness, conscientiousness, and openness to experience. Participants filled in the questionnaires on a laptop, taking up an average duration of ±15 minutes.

A custom-made trigger device was used, which was provided with three buttons: one button to simultaneously start the EEG recording on both devices (latency 1 ms, jitter 2-3 ms), one button to add synchronized markers to the acquisitioning EEG (latency 1 ms), and one button to play the auditory tapes from VLC Media Player software (latency 1 ms, jitter 2-3 ms). The device was connected via USBs to both acquisitioning computers. The individual earphones were also connected to the acquisitioning computers. Via the trigger device, the auditory listening tapes and EEG markers could be controlled simultaneously for both computers at once.

Procedure

Prior to EEG preparation, participants were asked to fill in the HEXACO-PI-R. Participants were instructed to keep both feet on the ground and to sit comfortably, yet upright in their chair. Before starting the experimental conditions, a simultaneous baseline rest-EEG was measured for each dyad (3 min). Dyads completed the tasks while their EEG was simultaneously recorded.

The experimental design consisted of a joint mindfulness task condition and a matched control condition (referred to as the individual mindfulness task). Throughout the experiment, participants were seated together in the same room, in the same position: face-to-face in a normal chair, approximately 90 cm away from each other. Conditions lasted 3 min and were separated by a 3 min break. The order of joint and individual conditions was counterbalanced over dyads. During the individual and joint mindfulness tasks, the same mindfulness listening tape was played. During the individual task, a screen (1.5 × 1.5 m) was placed between the two participants and the instruction was presented through earphones. In the individual task condition, participants were aware of the presence of the other participant at the other side of the screen, which only separated the participants visually, while they were still able to hear each other. To ensure that they were not aware of the other participant practicing mindfulness, they were told that the other participant had to perform an auditory attention task. During joint mindfulness, there was no screen and the listening tape was played through room stereos. This distinction was made to enlarge the notion of practicing joint mindfulness compared to the individual condition. However, during the actual task performance, all participants were instructed to close their eyes.

Electroencephalograph Processing

The EEG dynamics of all dyads was recorded using two Deymed Truscan 32-channel EEG amplifiers in combination with two 19-channel Ag/AgCl electrode caps, one for each participant. The electrodes were placed according to the International 10/20 System. Electrode skin impedance was kept below 10 kΩ. The raw 1024 Hz signal was downsampled to 128 Hz, while using a Notch filter 50/60 Hz, an antialiasing filter of 50 Hz, and a 1-40 Hz bandpass filter. Extra electrodes were placed on the left earlobe to serve as the ground and on the right earlobe to serve as the reference. In addition, electrodes were placed on the left and right upper ear helix, which were used for offline linked-ear reference. Each EEG system was connected to a separate portable computer from which the EEG dynamics were recorded using the Deymed Acquisitioning programme. Thus, for each dyad, two EEG systems and two portable computers were used.

Selection of artefact-free EEG data for further analysis was done by an EEG expert after screening for seizure activity and/or abnormal EEG patterns. Data files were screened for eye blinks, eye movement in vertical and lateral ways, technical flaws, and distortion by frontal and temporally located muscle contractions. To this end, the EEG expert visually inspected the EEG data and additionally used the program Persyst 14 (Persyst Development Corporation, San Diego) with the automated built in tool for spike analysis. For artifact rejection, the automated selection tool of another program (Neuroguide V3.0.0) was used. The default for eye movement and drowsiness selection is "high," which is the most sensitive setting, and 1.5 *SD*s threshold for the amplitude multiplier. The selection tool was set to use a normative database to select artefact free data. The *z* score of 1.5 *SD*s means that if at least one second of successive instantaneous *z* scores are equal to or less than 1.5 SDs, then a selection is made (Applied Neuroscience, 2018). After this process, the EEG expert visually checked for inconsistencies and false positives or negatives. This process was repeated by a second EEG expert for control. There were no signs of any abnormality. Data of individual EEG recordings were included only when there was a minimum of 20 seconds artifact-free data. Five different electrodes (F7, F8, Fz, T5, and T6) were analysed within the theta (4-8 Hz) and alpha (8-12 Hz) frequency band. We selected these electrodes to limit the number of tests and because they seem appropriate to represent frontal and temporal brain activity. To determine the intersubject coherence, the fast fourier transformation (FFT) analysis was used. The calculation of inter-subject coherences using FFT was done by measuring the degree of consistency in phase differences between two signals. The FFT spectrum is computed with 0.5 Hz resolution with the centre frequency at 0.25 Hz within a given frequency 0.5 Hz band. The frequency bands in the Neuroguide software do not have any gaps or overlaps, for example, frequency band 1.0 Hz to 2.0 Hz = 1.0 to 1.5 Hz + 1.5 Hz to 2.0 Hz. The adjacent frequency band: 2.0 to 3.0 = 2.0 to 2.5 Hz + 2.5 Hz to 3.0 Hz. The calculation was performed by the Neuroguide (V3.0.0) software. This application used the following formula to calculate interelectrode coherence:

$$Coherence\,(f) = \frac{\left(\sum_N (\mathrm{a(x)u(y)+b(x)v(y)})\right)^2 + \left(\sum_N (\mathrm{a(x)v(y)-b(x)u(y)})\right)^2}{\sum_N (\mathrm{a(x)^2+b(x)^2+b(x)^2}) \sum_N \mathrm{u(y)^2+v(y)^2})}$$

N and the summation sign represent averaging over frequencies in the raw spectrogram, averaging replications of a given frequency, or both. The numerator and denominator of coherence always refer to smoothed or averaged values, and when there are *N* replications or *N* frequencies, then each coherence value has 2*N* degrees of freedom. Note that if spectrum estimates were used, which were not smoothed or averaged over frequencies nor over replications, then coherence = 1. (Bendat & Piersol, 1980; Benignus, 1968; Otnes & Enochson, 1972). In order to compute coherence, averaged cospectrum and quaspectrum smoothed values with degrees of freedom > 2 and error bias = 1/*N* is used. (Thatcher et al., 2004)

In our study, these two signals originated from two exact same electrodes, yet from different subjects. Average FFT intersubject coherence was calculated for each condition, separately per electrode and frequency band.

Statistical Analyses

Two separate repeated-measures analyses of variance (ANOVA) were applied with personality trait (extraversion and agreeableness) as the between-subjects factor and condition (individual/joint) as well as electrode locations (F7, F8, T5, T6, Fz) as repeated measures. One analysis was applied for the theta and one for the alpha band. These analyses aimed to test whether the intersubject coherence during the joint mindfulness task was significantly different from the intersubject coherence during the matched individual mindfulness task condition and to test for the interaction between condition (joint/individual) and personality trait (high/low). In case of a multivariate main or interaction effect, post-hoc analyses were applied to test which specific location was significant. Post-hoc tests were one-tailed for the hypotheses specifying higher intersubject coherence during the joint condition and in higher agreeableness dyads. The between-subjects factors of agreeableness and extraversion were created by the SPSS procedure of visual binning. We used the visual binning option of equal percentiles, which resulted in one group consisting of subjects with high scores and one equally large group consisting of subjects with low scores. As the distribution of the intersubject coherence data was not normal, we applied a log-transformation, resulting in a normal distribution.

To ascertain that our 11 datasets provided enough power to detect the hypothesized effects, we conducted a power analysis for repeated-measures ANOVA using the program G*Power 3.1.9.4 (Faul et al., 2007). After applying an effect size $\eta^2 = 0.3$ (similar to $f = 0.65$), correlation = 0.2, two conditions (individual and joint), and 10 measurements (2 conditions, 5 electrode locations), the obtained power was 0.97 for a sample size of 6. The level of significance was set at $p \leq .05$. For all ANOVAs, we controlled the false discovery rate (FDR). We applied Benjamini-Hochberg correction with an FDR of 0.05. The FDR can be applied in smaller studies and has the advantage of increasing power when analyzing multiple tests. The practical implications and benefits of applying an FDR as compared to Bonferroni adjustments are described in an extensive review (Glickman et al., 2014).

As there appeared to be a number of outliers, we replaced 6 outliers by the nearest nonoutlier value. Outliers were defined as 1.5 × interquartile range. Out of the 10 dependent variables, one dyad had three outliers and three dyads had one outlier each. The procedure of replacing the values of extreme observations by the nearest unaffected values is called Winsorizing (Tukey, 1962). This practice results in estimators of the mean that are scarcely distinguishable from those of best linear estimators. Moreover, the obtained Winsorized means appear to be more stable than trimmed means. Specifically, under normality, the Winsorized mean is more efficient, as reflected by the ratios of variances of corresponding estimators than the trimmed mean for sample sizes 10 and 20 (Dixon, 1960; Dixon & Yuen, 1974). In line with this view, a computer simulation study on patient measurements (Bietenbeck et al., 2020) indicated that Winsorization of outlying values often led to a better performance than simple outlier removal. In addition, in relatively small sample sizes with three or more outliers present, Winsorizing offers a more accurate control of Type I error rates than a nonparametric test (Liao et al., 2016). Notably, Winsorizing has been applied in EEG studies regarding functional connectivity in infants (Haartsen et al., 2019), the detection of P300 potentials (Lotte et al., 2009), and the averaging of event-related potentials (Leonowicz et al., 2005).

Additionaly, with respect to frequency power, two separate repeated-measures ANOVAs were applied on the data of the individual participants ($n = 22$) with agreeableness as the between-subjects factor and condition (individual/joint) as well as spectral power (µVsq) at fivee electrode locations (F7, F8, T5, T6, Fz) as repeated measures. As the distribution of the individual spectral power data was not normal, we applied a log-transformation resulting in a normal distribution. One analysis was applied for the theta and one for the alpha band. These analyses aimed to test whether the spectral power during the joint mindfulness task was significantly higher than that during the individual mindfulness condition and to test for the interaction between condition (joint/individual) and agreeableness. In case of a multivariate main or interaction effect, post-hoc analyses were applied to test which specific location was significant. Post-hoc tests were one-tailed for the hypotheses specifying higher spectral power during the joint condition and in higher agreeable dyads.

RESULTS

Kolmogorov-Smirnov tests of normality indicated that all data were normally distributed within the factors of agreeableness and extraversion ($p < .05$), except for electrode Fz in the low agreeable group under the joint condition ($p = .007$).

A significant multivariate interaction between agreeableness and condition was found for the theta band of the five electrode locations, $F(1, 7) = 6.13$, $p = .042$, partial $\eta^2 = .47$. Also, with respect to the alpha band, a significant multivariate interaction between agreeableness and condition was found, $F(1, 7) = 5.92$, $p = .045$, partial $\eta^2 = .46$. As interactions between agreeableness and condition were significant for the theta and alpha bands as well, we performed an additional repeated-measures ANOVA with all 10 electrode locations as dependent variables. Results indicated a significant interaction between agreeableness and condition, $F(1, 7) = 11.24$, $p = .012$, partial $\eta^2 = .62$. For most locations, the high agreeableness group showed an increase in intersubject coherence, which was opposite to the coherence change in the low agreeableness group (see Figure 1)

In addition, results indicated a significant multivariate main effect for condition on the alpha band, $F(1, 7) = 6.49$, $p = .038$, partial $\eta^2 = .48$. Tests on the separate electrode locations indicated significant interaction effects between agreeableness and condition for electrode T6 in the theta band, $F(1, 9) = 7.59$, $p = .01$, partial $\eta^2 = .46$ and for electrode Fz in the theta band, $F(1, 9) = 5.05$, $p = .05$, partial $\eta^2 = .36$. After the Benjamini-Hochberg correction, only the interaction effect for electrode T6 remained significant. No significant interaction effect was found for any of the separate electrodes in the alpha band. Results indicated that particularly in the high agreeableness group, EEG theta coherence in the joint condition was larger than in the individual condition (see Figure 2). The log-transformed coherence of the individual dyads is shown in Figure 3. Levene's test of equality of error variances indicated that for all analyses, the error variance of the dependent variable was equal across groups ($p > .05$).

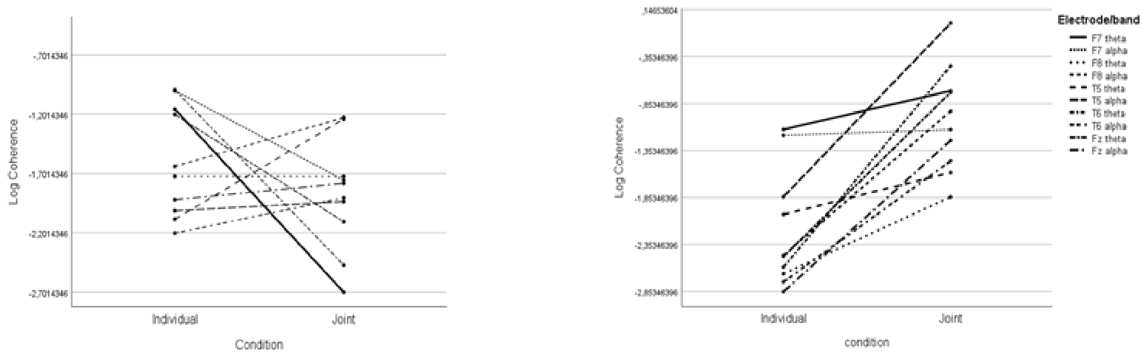

FIGURE 1.

Mean coherence under the individual and joint condition for all electrodes and frequency bands in low (Left) and high (Right) agreeable groups.

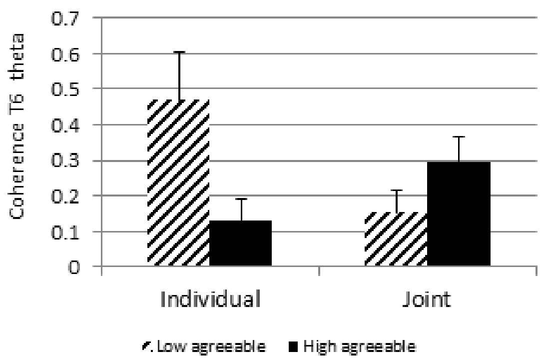

FIGURE 2.

Mean coherence (+ SE) for electrode T6 theta band under the individual and joint mindfulness condition for low and high agreeable groups.

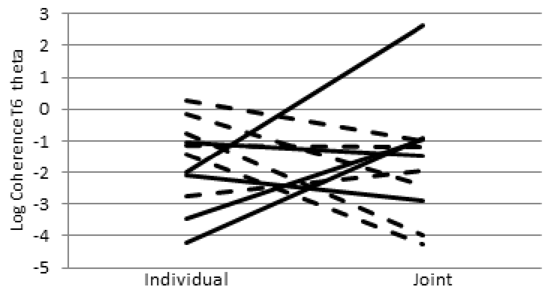

FIGURE 3.

Mean log coherence for electrode T6 theta band under the individual and joint mindfulness condition for individual low (dashed lines) and high (solid lines) agreeable subjects

With respect to the main effect of condition, tests on the separate electrode locations indicated significant main effects of an increase in intersubject coherence during the joint mindfulness task compared to the individual mindfulness task for electrode F8 in the alpha band, $F(1, 9) = 6.56$, $p = .02$, partial $\eta^2 = .42$, for electrode T5 in the alpha band, $F(1, 9) = 5.93$, $p = .02$, partial $\eta^2 = .40$, and for electrode T6 in the alpha band, $F(1, 9) = 5.42$, $p = .02$, partial $\eta^2 = .38$. The mean, *SD*s and ps for all main effects are shown in Table 1.

In addition, a repeated-measures ANOVA revealed no significant interaction effects between the factors of extraversion (high/low) and condition (individual/joint mindfulness) on EEG coherence.

With respect to frequency power, Kolmogorov-Smirnov tests of normality indicated that all log spectral power data were normally distributed ($p < .05$), except for electrode T6 in the theta band under the joint condition ($p = .03$). Results indicated a significant multivariate main effect for condition on the alpha band, $F(1, 20) = 4.37$, $p = .05$, partial $\eta^2 = .18$. With respect to the separate electrode locations, a significant main effect of an increase in spectral power during the joint mindfulness task compared to the individual mindfulness task was found for electrode F8, $F(1, 20) = 4.16$, $p = 0.03$, partial $\eta^2 = .17$. After the Benjamini-Hochberg correction, this effect for electrode F8 was not significant any more. As is shown in Figure 4, except for F7, spectral power values (μVsq) were higher in the joint condition. In addition, a repeated-measures ANOVA revealed no significant main effect for condition on the theta band nor any interaction effect between agreeableness (high/low) and condition (individual/joint mindfulness) on alpha or theta band power.

DISCUSSION

The main objective of this study was to evaluate the effects of the joint mindfulness task on intersubject coherence. We were interested in whether we could find neurophysiological arguments for joint mindfulness, a therapy method that is increasingly being used for stress reduction. Interestingly, we have indeed found an increase in intersubject coherence during the joint mindfulness task compared to the

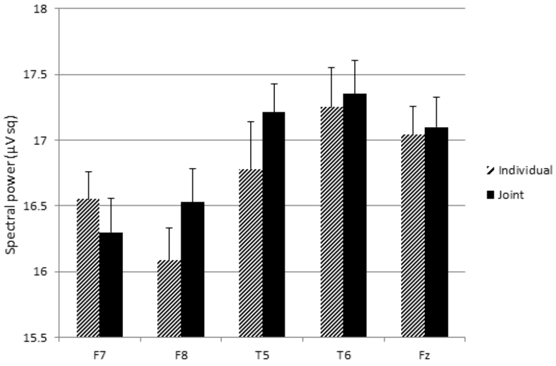

FIGURE 4.

Mean log spectral power (μVsq) values (+ SE) for the alpha band under the individual and joint mindfulness condition.

individual mindfulness task in frontal and temporal electrodes in the alpha band. The finding that joint mindfulness increases intersubject coherence particularly with respect to the alpha band is partly in agreement with results of studies using social cooperative tasks (Astolfi, Toppi, Borghini, et al., 2011; Astolfi, Toppi, De Vico Fallani, et al., 2011; Babiloni, Astolfi, et al., 2007; Kawasaki et al., 2013; Lindenberger et al., 2009; Liu et al., 2016; Muller et al., 2013; Toppi et al., 2016). In these studies, increases in intersubject coherence were not only observed in the alpha but also in theta frequency bands in frontal and temporal regions.

It may be argued that the present results are only the consequence of the face-to-face setting, while the mindfulness training itself has (hardly) any additional effect. However, it should be stated that, irrespective of the impact of the listening tape, participants were actually performing the mindfulness instructions. Thus, the present results are at least associated with some kind of mindful breathing exercise. Moreover, as mentioned in the Introduction section, mindfulness seems to be associated with an increase in theta, while an increase in alpha activity may, in addition to mindfulness activity, reflect relaxation, mind-wandering, a resting state with closed eyes, and a lower level of social interaction (Aftanas & Golocheikine, 2001; Morse et al., 1977; Novembre et al., 2016). As In the present study participants were facing each other with eyes closed, the observed increase of coherence in the alpha band during the joint mindfulness task may indicate that the listening tape leads to an increase in shared relaxation, instead of an increase in shared mindfulness. It may be true that the mindfulness listening tape that we used in the present study did not induce mindfulness but only relaxation in a subgroup of participants. As a consequence, a mutual increase of alpha power as a result of increased relaxation may have led to an increase in coherence in the alpha band. Thus, the present results averaged across all dyads suggest an increased intersubject coherence in the alpha band as a result of an increased shared relaxation. It may also be claimed that the intersubject coherence simply reflects joint respiration within dyads. However, in the first place, participants were instructed to focus on their own breathing, and there was no instruction on how to breathe. So, each participant could maintain their own specific breathing frequency. Furthermore, respiration has been found to modulate the power of gamma oscillations, that is, increases in the power of gamma oscillations (40–100 Hz) during certain phases of the respiratory cycle (Heck et al., 2017). In addition, slow breathing has been found to decrease higher beta activity (15-32 Hz) in frontal brain areas, while delta, theta, and alpha activity did not change (Chen et al., 2017). In contrast to these two studies, no modulation of EEG bandpower was found in high-density EEG recordings from twelve healthy subjects, who were instructed to alternate between fast and slow breathing (Chaoul & Grosse-Wentrup, 2015). Thus, as we focussed on theta and alpha activity and only examined changes in coherences in these frequency bands, we may conclude that the observed increases in coherence are not merely reflecting joint respiration. In addition, we aimed to assess whether the personalities of the interacting dyads had an influence on intersubject coherence during the joint mindfulness task. We decided to investigate two personality dimensions, agreeableness and extraversion, as they have been shown

TABLE 1.

Mean coherence values, *SD* and *p*s (one-tailed) for the individual and joint mindfulness condition.

		Individual mindfulness		Joint mindfulness			
Electrode	Frequency	*M*	*SD*	*M*	*SD*	*N*	p[a]
F7	Theta	0.55	0.62	0.23	0.21	11	0.37
F7	Alpha	0.50	0.56	0.34	0.31	11	0.40
F8	Theta	0.23	0.24	0.24	0.23	11	0.43
F8	Alpha	**0.23**	**0.28**	**0.40**	**0.26**	**11**	**0.02**
Fz	Theta	0.32	0.41	0.28	0.28	11	0.57
Fz	Alpha	0.17	0.18	0.36	0.34	11	0.10
T5	Theta	0.29	0.40	0.60	0.75	11	0.63
T5	Alpha	**0.29**	**0.32**	**0.53**	**0.45**	**11**	**0.02**
T6	Theta	0.31	0.31	0.22	0.16	11	0.76
T6	Alpha	**0.13**	**0.13**	**0.30**	**0.27**	**11**	**0.02**

Benjamini-Hochberg significant p value is shown in bold

[a] = Based on repeated measures ANOVA between the individual and joint mindfulness

to be associated with friendship and positive interpersonal interactions (Jensen-Campbell et al., 2002). With respect to extraversion, no interaction with intersubject coherence was found. However, we found that higher agreeableness within a dyad was associated with an increase in coherence in the temporal theta band, which may reflect a shared increase in theta activity as a result of induced mindfulness. These findings suggest that only in the high agreeableness group, the mindfulness tape induced a state of mindfulness, which in turn resulted in higher intersubject coherence in the theta band. The present finding of an increase in intersubject coherence in temporal theta and alpha band is supported by a number of studies on social cooperative tasks, which found increases in intersubject coherence in temporal alpha and theta frequency bands (Astolfi, Toppi, Borghini, et al., 2011; Astolfi, Toppi, De Vico Fallani, et al., 2011; Kawasaki et al., 2013; Lindenberger et al., 2009; Liu et al., 2016; Muller et al., 2013; Toppi et al., 2016). The increase we found in intersubject coherence in the frontal and temporal theta and/or alpha band might be associated with ToM activation, as this network includes frontal and temporal areas and seems to be involved in social interactions (Schurz et al., 2014). Moreover, as was mentioned in the Introduction section, intersubject coherence appeared to increase in frontal and temporal alpha and theta frequencies during the performance of cooperative tasks which require ToM abilities. Finally, as agreeableness is correlated with social-cognitive ToM performance, the finding that particularly agreeableness within a dyad was associated with an increase in intersubject coherence in theta band may suggest the involvement of ToM. Notably, the increased alpha spectral power at the multivariate combination of frontal and temporal electrodes in the joint condition provides some support for the activation of ToM areas. As we did not find an interaction effect of agreeableness and condition on spectral power, we could not prove the association of ToM with agreeableness.

CONCLUSIONS

We may conclude that intersubject coherence increases during joint mindful breathing. This is especially true concerning subjects with high agreeableness. However, it must be stressed that the approach of the present study had some exploratory features. The objective was to get an impression of the most important changes in intersubject coherence under different conditions. The present results should be confirmed in future studies that test more specified hypotheses to clarify or falsify our results.

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