Brain Functional Connectivity Correlates of Anomalous Interaction Between Sensorily Isolated Monozygotic Twins

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Abstract

This study examined brain functional connectivity (FC) changes associated with possible anomalous interaction between sensorily isolated monozygotic twins. Brain FC was estimated using the Steady State Visual Evoked Potential-Event Related Partial Coherence (SSVEP-ERPC) methodology. Five twin pairs served twice as participants with an average interval between sessions of 67 days. In each recording session, one twin, the 'Sender', viewed a randomized set of 50 general images and 50 personally relevant images, whilst the other twin, the 'Receiver', viewed a static personally relevant image for the entire duration of the session. Images were presented to the Sender on the screen for 1.0sec with the interval between successive images varied randomly between 4.0 and 8.0 sec. It was hypothesized that anomalous interactions would be indicated by statistically significant receiver FC changes when those changes are determined using the sender image appearance times. Receiver FC changes were calculated from the appearance times of the images as viewed by the Sender. For each twin serving as Receiver, FC components were separately analysed for the general and personal images, yielding 38 observations (19 twin pairs by 2 conditions). The hypothesis was confirmed in that 12 of the 38 observations yielded statistically significant Receiver FC increases (10 cases) or decreases (4 cases) at the $p<0.01$ level only when trials were synchronized to the Sender image appearance times. Overall, this effect was significant at the $p=4X10^{-8}$ Df=175. To the best of our knowledge, this is the first study reporting statistically significant FC changes indicative of anomalous interactions between two sensorily isolated individuals.

Keywords

Brain functional connectivity; anomalous interactions, monozygotic twins; SSVEP-ERPC

Introduction

Identical (monozygotic) twins have long been a topic of popular interest, if not intrigue. One aspect of such interest are claims that identical twins are more likely to report anomalous 'shared experiences' [1]. An anomalous experience can be defined as the sharing or communication (through information, images, or emotions) between separate minds [2, 3]. Typical of such anomalous shared experiences are claims that one twin experienced somatic pain or discomfort at the same time their sibling was involved in a mishap or accident, even though the twins may be separated by a long distance [1]. It is therefore unsurprising that research into anomalous interactions remains of interest.

A number of studies have examined experimental evidence for electroencephalographic (EEG) or functional Magnetic Resonance Imaging (fMRI) indications of correlated brain activity in pairs of individuals sharing an emotional bond such as a family relationship, friendship or a romantic relationship [1, 4-9]. Typically, simultaneous brain activity is recorded from a pair of sensorily isolated individuals and one of the pair, the 'Sender' is exposed to a stimulus or a task. Anomalous interactions between the individuals are thought to be indicated by concurrent brain activity changes in the other participant, the 'Receiver'. One of the earliest EEG studies of anomalous interaction in sensorily isolated twins involved the 'sender' closing their eyes at various times to increase EEG alpha activity [4]. A concurrent EEG alpha activity increase in the receiver twin was considered evidence of anomalous interaction, with this effect reported in 2 of the 15 pairs of twins examined. A more recent fMRI study of a pair of monozygotic twins explored changes in brain activity during auditory and visual tasks [10]. The Receiver was in the fMRI scanner, while the Sender passively viewed either emotional and personally relevant images, or heard sounds chosen to elicit fear. Both the visual and auditory task presentations were 260 sec in duration and comprised 20 sec stimuli followed by 20 sec rest intervals. Findings illustrated statistically significant increases in Receiver brain activity at left orbitofrontal gyrus, left cingulum, and left precentral gyrus at times the Sender was engaged in the auditory or visual perception tasks. Together, these studies provide support for the reality of such anomalous interactions.

While the majority of studies have reported evidence consistent with enhanced correlated brain activity in pairs of emotionally related individuals [2, 5-7, 10-12], others have either failed to replicate these findings [13, 14] or have been criticized on the basis of small numbers of participants [15]. Primarily, these studies have implemented tasks with little or no emotionally relevant stimuli, such as Zener cards [16, 17]. However, past research has demonstrated that anomalous shared experiences tend to be personally relevant and emotional, rather than neutral [1, 18]. Therefore, is it theorized that the inclusion of personally relevant emotional stimuli may yield a stronger effect.

To date, the two main brain imaging methodologies that have been used to study inter brain anomalous interactions have been EEG and fMRI. The current study breaks new ground in being the first to examine dynamic changes in brain functional connectivity (FC) that may indicate the presence of anomalous interbrain interactions. This approach is novel in applying the evoked potential methodology Steady State Visual Evoked Potential Event Related Partial Coherence (SSVEP-ERPC) to measure brain FC changes indicative of anomalous interbrain interactions.

The choice of SSVEP-ERPC was based on several factors. Firstly, unlike fMRI, the methodology offers high temporal resolution estimates of brain FC, thus enabling one to

identify cognitive task components associated with specific FC changes [19]. Additionally, the SSVEP-ERPC is highly resistant to the most common sources of EEG noise and artifacts [20]. Finally, the methodology has been found to be especially sensitive to FC changes associated with cognitive processes, such as attentional and hyperactivity components of ADHD [21-23]. The technology has also contributed novel findings concerning the dynamic features of brain connectivity networks that mediate the process of creative originality [24].

In the current study, changes in brain FC were examined in five pairs of monozygotic twin females, comprising a series of single pair (Sender and Receiver) studies. In this paper the twin viewing the images will be referred to as the 'Sender' and the other as the 'Receiver'. Fifty of the images portrayed landscapes (non-personal images) while the remaining 50 were images provided by each set of twins and were selected as being of personal or emotional relevance to the twins (personal images). The critical metric we will be evaluating is the presence of statistically significant event FC changes in the Receiver when we use the image presentation times as viewed by the Sender.

Hypothesis 1.

The presence of anomalous interactions between monozygotic twin pairs will be indicated by statistically significant time dependent FC changes in the Receiver when the received event related FC is calculated using the image presentation times of the Sender.

Hypothesis 2.

In the event that statistically significant Receiver FC changes are observed, these will be larger for the personal images, when compared to non-personal images.

Material and methods

Ethics approval and informed consent.

Informed consent was obtained from all participants, and from guardians of participants aged under 18 years. Ethics approval for the study was obtained from Swinburne University of Technology Human Ethics Research Board (# SHR Project 2018/416).

Scheduling

All twins participated in two recording sessions. Recording sessions took place in Nov 2022 (Session 1) and Jan-Feb 2023 (Session 2).

Each participant acted as Sender and Receiver in the recording sessions, with participants randomly assigned roles.

Participants

To be eligible for participation, individuals were required to be monozygotic twins aged 13 years or older. Monozygosity was determined through DNA testing that was made available to all twins participating in the study. The final sample consisted of 5 pairs of female

monozygotic twins. The results of monozygosity testing and age of participants are provided below.

Table 1,

	Pair 1	**Pair 2**	**Pair 3**	**Pair 4**	**Pair 5**
Age	21 years	13 years	27 years	39 years	17 years
MZ probability %	99.9999998	99.99999999773	99.99999999766	99.99999999695	99.99999999339

Participants were also required to have shared at least one anomalous experience with their twin and were available to attend the same testing session with their twin. Exclusion criteria included, pregnancy, epilepsy, a history of head trauma, or a current or past diagnosis of schizophrenia or dissociative disorder.

Visual Stimuli

Visual stimuli presented during the recording tasks included 50 personally relevant and 50 general images. All visual stimuli were presented on a black background. Each participating pair was asked to provide no more than 50 and no less than 25 personally relevant images. Personally relevant images were defined as photographs representing something significant or meaningful to the twin pair. Where necessary, personally relevant images were randomly repeated to reach 50 trials. All personally relevant images provided by participants were treated with confidentiality.

Fifty general images were sourced from a free online database. These images included landscape and natural scenery stimuli. Each participant viewed the same set of general images in a unique random order.

Procedure

Participants attended two 90-minute sessions roughly two months apart ($M_{interval}$ = 67 days). Each session included recording tasks, followed by a series of questionnaires.

Session 1 Procedure

After providing informed consent, participants were randomly and blindly assigned the role of Sender or Receiver. Participants were then seated in separate rooms roughly eight meters apart. Rooms did not share any walls and were further isolated by three closed doors.

Participants were seated approximately 60 centimeters from a 32-inch screen, in a quiet dark room. Participants were informed that they would be presented with one or more images on a screen and were instructed to tap into a time that they felt in tune with their twin (see Supplementary material for the complete script).

During Session 1, twin pairs completed two recording tasks, serving successively as Sender and Receiver or in the reverse order. Following the first task, participants swapped both rooms and roles before being reinstructed with the script. A brief procedural outline for each role is as follows.

Sender

The Sender was presented with 100 visual stimuli comprising both general and personally relevant images. Each image appeared on the screen for 1.0 second. The appearance of each image was followed by a 4.0 second fixed interval and a unique random interval 0.0 second – 4.0 second determined by a TrueRNG random number generator ($M_{interval}$ = 6.0 sec; *SD* = 1.2 sec). Image order was uniquely randomized for each twin using the Matlab Randperm function, with the task lasting roughly 11 minutes. While the average interval between successive images was 6 sec (*SD* = 1.2 sec), the average interval between successive general or personal images was 12 sec (*SD* = 2.4 sec).

Receiver

The Receiver was presented with one personally relevant visual stimulus depicting both twins. The presentation of this image remained for the entire task, lasting approximately 11 minutes.

Each participant was reimbursed $200 for their time in Session 1.

Session 2 Procedure

Session 2 followed the same procedure as Session 1 recording with the following two differences. The two image sequences viewed by the Senders in Session 1 were swapped in Session 2. In other words, the image sequence viewed by Sender 1 in Session 1 were now viewed by Sender 2 in Session 2 and vice versa. The second difference was the inclusion of an additional recording component at the end of the sender-receiver recordings. This was an 11-minute control recording where both twins viewed a single image. During this time, twins were instructed to passively view the image. This final task acted as an additional control component.

Each participant was reimbursed $200 for their time in Session 2.

Data acquisition and the Steady State Visual Evoked Potential (SSVEP)

Brain electrical activity was recorded from 20 scalp sites in line with the International 10-10 system [25]. The average potential of both mastoids served as a reference, while an electrode located at FPz served as a ground. Brain electrical activity was amplified and bandpass filtered (3 dB down at 0.1 Hz and 30 Hz) before digitization to 16-bit accuracy at a rate of 400 Hz. The major features of the signal processing have previously been described (see [21] for further details.

A three-step process was used to calculate the steady state visual evoked potential (SSVEP). The first step involved band-pass filtering the sampled data (11.0 Hz – 15.0 Hz) using the fast Fourier transform. For the second step, the discrete Fourier transform was used to determine the real and imaginary single cycle Fourier coefficients at the 13Hz stimulus frequency. The final step involved smoothing the real and imaginary Fourier coefficients with a cosine

weighted smoothing window 23 stimulus cycles in length. The equivalent or rectangular window width is half the duration of the cosine width or 12 cycles. The cosine smoothing window was then shifted 1 stimulus cycle and the coefficients were recalculated for this overlapping period. This produced the SSVEP and was continued until the entire 380 seconds of activity was analysed. An identical procedure was applied to data recorded from all recording sites.

SSVEP Event-Related Partial Coherence (SSVEP-ERPC)

Functional connectivity (FC) between electrode sites was determined using an approach termed SSVEP Event Related Partial Coherence (SSVEP-ERPC). This approach is a measure of the partial coherence between electrode pairs at the stimulus frequency eliciting the SSVEP [19] and is based on a modification first described by Andrew and Pfurtscheller [26]

Partial coherence varies between 0 and 1 and like coherence, is a normalized quantity that is not determined by the SSVEP amplitude at either electrode site. Electrode pairs with high partial coherence indicate relatively stable SSVEP phase differences between electrode pairs across trials. This occurs even though SSVEP phase differences between each of the electrodes and the stimulus may be variable across trials and is equivalent to the removal of the common contribution from the SSVEP stimulus. Therefore, the high SSVEP partial coherence between electrodes reflects a consistent synchronization between electrodes at the stimulus frequency, rather than a consequence of two unrelated regions increasing their response to the common visual flicker. Such synchronization reflected in the SSVEP-ERPC is thought to reflect FC between the relevant regions, with the terms 'SSVEP-ERPC' and FC used interchangeably.

For each Sender and Receiver, the SSVEP-ERPC was calculated for all 190 distinct pairs of electrodes averaged for both the personal image presentation times and the general image presentation times as viewed by the Sender in each of the recording sessions. In both cases, personal and general images, the SSVEP-ERPC was calculated for a 5 sec epoch commencing 2.0 sec before the appearance of an image.

Statistical analysis.

To test the hypotheses, a permutation test was used to determine the extent to which the maximum and minimum values of the individual Receiver FC were most likely to occur when the receiver event-related FC was calculated on the basis of the image appearance times as viewed by the Sender. Specifically, for each case per session (50 general or 50 personal images as viewed by sender), the observed FC for all unique combinations of the 20 electrodes or 190 combinations were initially ascertained. To test the NULL hypothesis that the observed FC values could have occurred by chance an array of random presentation times with a mean inter-image interval of 12 sec were generated.

For each permutation, the surrogate FC measures were calculated and subsequently used to determine whether the surrogate FC was equal to or exceeded the observed FC. This was repeated 10,000 times and the proportion of surrogate FC measures equal to or exceeding the observed value was taken as the exact probability (p_i) that the observed FC measure could have been exceeded by chance. This approach enabled the probability of observing a low FC value by chance to be determined. Thus, if 99% of the surrogate FC values exceeded the observed FC value (ie p_i=0.99), then the probability of observing the low FC value was 1- p_i =0.01. Therefore, this approach enabled the individual statistical significance of FC maxima

and minima to be determined. This was an important feature of the approach, as both FC increases and decreases played an important role in neural information processing [27]. This process was repeated for all 190 FC measures and for all points in time for the 5.0 sec epoch.

The next stage in the statistical analysis was to calculate the number of FC measures that were statistically significant at the 0.01 level. This selection of $p \leq 0.01$ rather than the $p \leq 0.05$ level, accounted for the multiple comparisons arising from the 5 sec FC epoch comprising 65 observations. Such adjustments are most commonly achieved using a Bonferroni correction where the nominal level for statistical significance, typically $p=0.05$ is divided by the number of independent observations. However, the 65 points of the FC time series are not statistically independent, with neighbouring points being highly correlated due to the cosine smoothing window. To determine the effective number of degrees of freedom the e-folding time determined from the autocovariance of the smoothed SSVEP phase time series was used [28]. Equation 1 relates the e-folding time to the effective number degrees of freedom.

$$Df=N/(2\ \text{e-fold}) \qquad 1.$$

Where Df is the number of degrees of freedom, N is the number of observations, 65 and e-fold is the number of cycles over which the autocovariance decays to 1/e of its maximum value. The e-folding time in cycles for all electrodes was found to be 7 cycles. In this case, the number of degrees of freedom for each 65-point time series is (65/(2*7) or 4.64. By taking $p \leq 0.05$ as the threshold for statistical significance of the permutation test, then the p-value adjusted for the multiple comparisons is: $p=0.05/4.65$ or $p \leq 0.0108$, which was rounded down to $p \leq 0.01$.

Statistical analysis, Number of significant individual FC results (NSFC)

The next stage of the individual statistical analysis involved determining the number of observed FC measures out of 190 that were individually significant at the $p_i \leq 0.01$ (FC maxima) or $p_i \geq 0.99$ (FC minima). A permutation test was then used to determine the statistical significance of observing a given number of FC measures each satisfying the condition $p_i \leq 0.01$or $p_i \geq 0.99$. This was determined separately for the 50 personal image times and the 50 general image times as viewed by the Sender. To test the NULL hypothesis that the observed number of FC values satisfying the above p_i criteria (maxima and minima) could occur by chance, an array of random presentation times using the same mean inter-image interval of 12 sec were generated.

For each permutation, the number of surrogate FC maxima and FC minima that satisfied the conditions $p_i \leq 0.01$ or $p_i \geq 0.99$ were determined. This was repeated 10,000 times and the proportion of times that the number of surrogate FC measures satisfying the conditions of $p_i \leq 0.01$ or $p_i \geq 0.99$ was taken as the exact probability (p_g) of observing this number of FC maxima or minima by chance.

Results

Whilst the principal focus of this report was exploring the changes in Receiver FC, the presentation format with an example of Sender FC changes in a participant were illustrated.

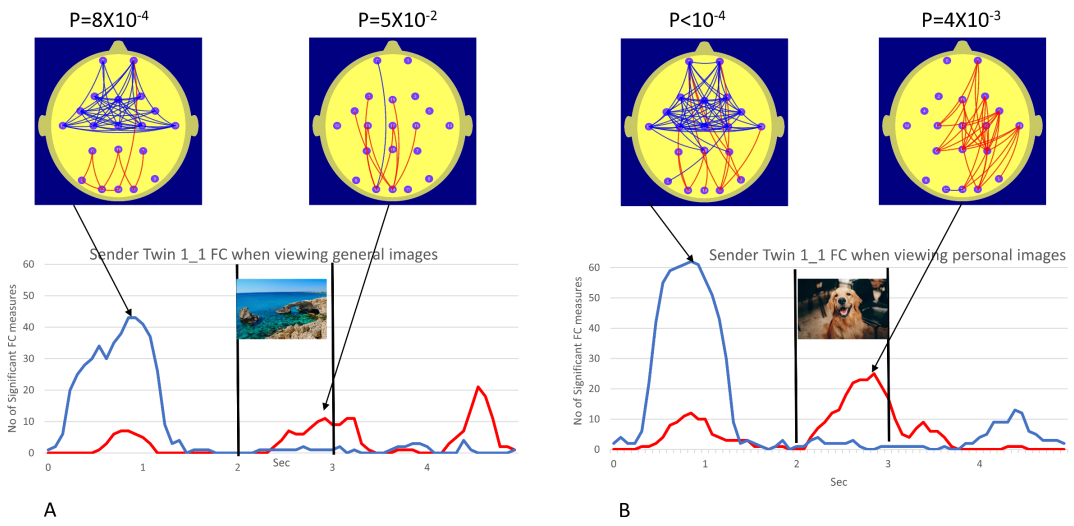

Fig 1. Sender data.
Fig 1A (left plots) illustrates the number of FC measures (NSFC) satisfying conditions $p \leq 0.01$ (red trace) and $p \geq 0.99$ (blue trace) in Sender 1_1 FC when viewing the 50 general images. Fig 1B (right plots) illustrates the equivalent for Sender 1_1 viewing 50 personal images. The vertical bars at the 2.0 and 3.0 sec mark indicate the duration of the image (1.0 sec) while the beach scene image is used to represent the general images and the dog image represents personal images. The red arcs of the brain map illustrate the topography of FC measures satisfying conditions $p<0.01$ (red) and $p>0.99$ at a point in time corresponding to peak values in NSFC plot. The statistical significance of NSFC peak values is indicated by the '*p*' value above the maps. The *p* value applies to whichever parameter exceeds the threshold NSFC value corresponding to $p<0.01$.

Significant FC increases and decreases in both cases were observed for participant Sender 1_1, although this effect appeared larger for the personal images. Interestingly, prominent FC reductions prior to the appearance of the next image were observed for both the general and personal images. This may be suggestive of an anticipatory effect. It should be noted that these FC changes occur in the person viewing the images, as such these do not represent any evidence for anomalous interactions.

Each Receiver participant recording session yielded a result for the 50 general images and 50 personal images. Thus, in Session 1, the 10 participants yielded a set of 20 individual receiver findings. In Session 2, equipment malfunction resulted in 9 participants yielding a set of 18 individual receiver findings. Thus, both sessions yielded a total of 38 individual receiver findings. Of the 38 individual findings, 26 did not exhibit statistically significant FC changes according to the threshold criteria while the remaining 12 individual findings exhibited at least one statistically significant NSFC peak.

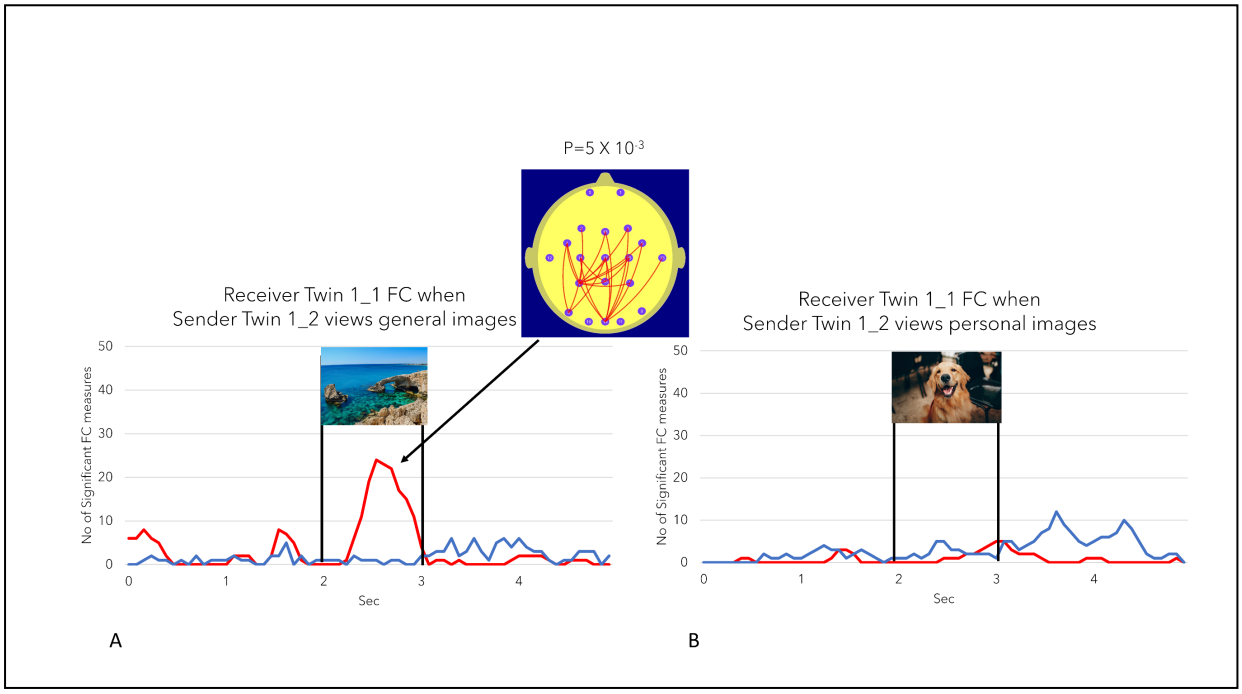

Fig 2. Receiver data.
Fig 2A (left) illustrates the number of FC measures (NSFC) satisfying the conditions described in Fig 1 for Receiver 1_1 FC when Sender 1_2 was viewing the general images. Fig 2B (right) illustrates the same Receiver 1_1 FC measures when Sender 1_2 was viewing the personal images. In Session 2, or the repeat session, Receiver 1_1 again exhibited a significant NSFC value in the 2-3 sec interval although in that case, it occurred when Sender 1_2 was viewing personal images.

When Sender 1_2 was viewing the general images, 24 FC maxima that are individually significant at the $p \leq 0.01$ level were observed. Overall, this number of FC measures individually satisfying the basic threshold was significant at the $p=5X10^{-3}$. In this case, the FC increases are primarily occipito-parietal to frontal. By contrast, when Sender 1_2 was viewing personal images, neither the number of FC increases or decreases reached statistical significance at the $p \leq 0.01$ level. The figure on the right is a typical example of a non-significant finding where neither the number of FC maxima or minima reached significance at the $p \leq 0.01$ level. Interestingly, in Session 2, Receiver 1_1 again demonstrated significant increase in the number of FC measures satisfying the positive threshold condition ($p \leq 0.01$) in the 2 – 3 sec interval in one of the conditions. However, in Session 2, the statistically significant effect was observed only when Sender 1_2 was viewing personal images.

The patterns of FC changes demonstrated large inter-individual variation. Fig 3 illustrates another statistically significant individual result. The figure on the left illustrates FC changes in Receiver 3_2 during Session 1 when Sender 3_1 was viewing personal images in this session. In this case, the early FC decreases were primarily located at left temporal to prefrontal sites while the later FC increases exhibited bilateral temporal to prefrontal increases. By contrast, Receiver 2_2 in Session 2 exhibited an early FC increase with a left parieto-temporal to frontal and central sites with a later more extensive bilateral FC decrease. The dotted line in the right figure illustrates the number of significant FC changes (maximum

of either positive or negative) during the Session 2 control condition when both twins are viewing a static image for 11 min. At no stage during of the control conditions did the number of significant FC measures (NSFC) reach statistical significance at the $p \leq 0.01$ level.

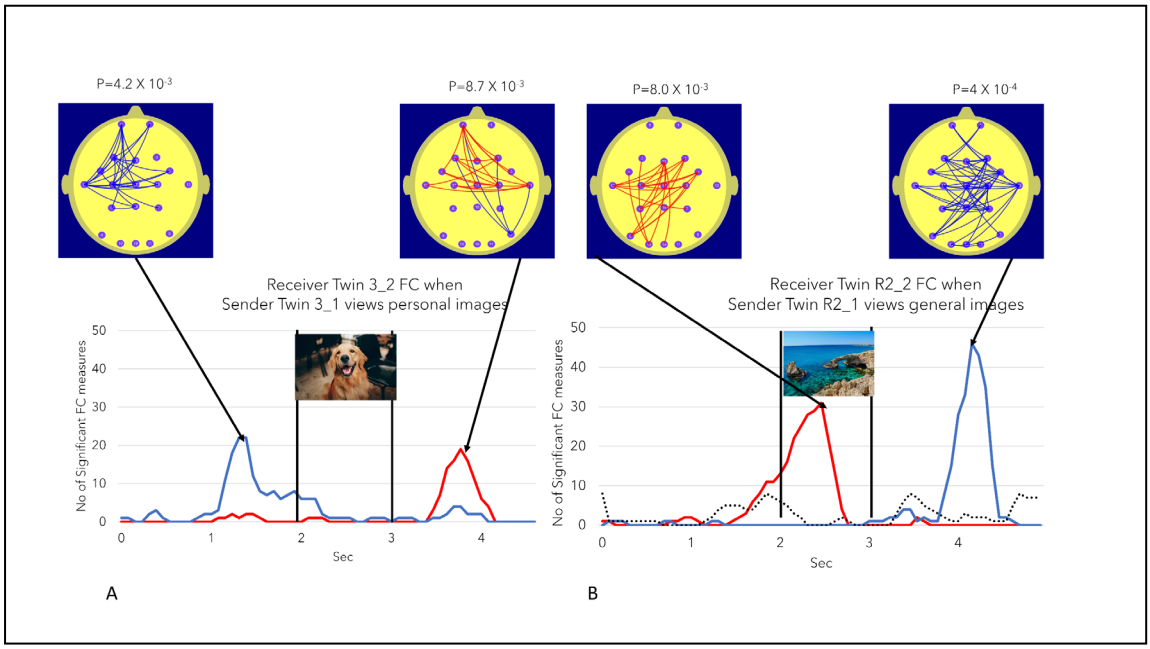

Fig 3. Receiver data.
Figs 3A and 3B illustrate the variations in FC increase or decrease, FC topography and the timing of these FC changes in two participants. Fig 3A illustrates significant findings in Receiver 3_1 when Sender 3_2 was viewing personal images. Fig 3B illustrates the equivalent finding for Receiver 2_2 during session 2 or the repeat session ie Receiver 2_2 when Sender 2_1 is viewing general images. The dotted line in Fig 3B represents the NSFC measure during the Session 2 control task when both twins were simultaneously viewing a static image for 11 min. The dotted line took the value of the maximum number of significant FC values (maxima or minima). In none of the Session 2 control task sessions did the number of significant FC values reach the $p \leq 0.01$ level.

The following table summarizes the statistically significant findings across sessions in the Receivers.

	Session 1 Senders viewing		Session 2 Senders viewing	
	General Images	**Personal Images**	**General Images**	**Personal Images**
Receivers	***p* value**	***p* value**	***p* value**	***p* value**
1_1	$5.0X10^{-3}$	n.s.	n.s.	$4.3X10^{-3}$
1_2	n.s.	n.s.	n.s.	n.s.
2_1	$6.9X10^{-3}$	n.s.	n.s.	$5.3X10^{-3}$
2_2	n.s.	n.s.	$8X10^{-3}$, ($6X10^{-4}$)	n.s.
3_1	n.s.	$9.1X10^{-3}$	n.s.	n.s.
3_2	n.s.	($4.2X10^{-3}$), $8.7X10^{-3}$	NA	NA
4_1	n.s.	n.s.	n.s.	n.s.
4_2	n.s.	$4.0X10^{-3}$	($3.2X10^{-3}$)	n.s.
5_1	($4.7X10^{-3}$)	n.s.	n.s.	n.s.
5_2	n.s.	n.s.	n.s.	$5.9X10^{-3}$, $9X10^{-3}$

n.s., = not significant

NA = no accessible data

Table 2 Findings listed in brackets refer to significant effects due to FC decreases while the others refer to corresponding FC increases.

To summarize, in the 38 individual sessions, 7 cases where p was equal to or less than 0.01 and greater than 0.005, ($0.005 \leq p < 0.01$) and 7 cases where $p \leq 0.005$ were observed. Todetermine the experiment wide statistical significance of these findings, the trinomial distribution was used. To determine the overall number of degrees of freedom we note that each individual 5.0 sec epoch is associated with 4.6 degrees of freedom. With 38 individual findings and 4.6 degrees of freedom per individual finding, the experiment wide number of degrees of freedom was estimated as 38 X 4.6 or 174.8 rounded up to 175.

The trinomial distribution yielded an overall $p=4 \text{ X } 10^{-8}$ with Df=175. Calculating the experimental effect size, Cohen's d equivalent using the approach described by Rosenthal & Rubin [29] yielded the following:

Cohen's d=0.87, considered a large experimental effect size [30].

We observed 8 cases where statistically significant FC changes were observed in the Receiver FC when the Sender was viewing personal images and 6 equivalent cases where the sender was viewing general images. A binomial distribution indicated this difference was not statistically significant p=0.2 Df=14.

While there were large inter-individual differences in the FC topography in the statistically significant individual findings, the following briefly summarizes the main topographic FC features we observed. Of the 14 significant findings, 10 were associated with FC increases and 4 FC decreases. A binomial distribution indicated that this difference approached but did not reach statistical significance, p=0.06, Df=14. In terms of hemispheric differences, 6 statistically significant individual FC findings were located predominantly in the left

hemisphere, 5 extended bilaterally, while 3 were restricted to the right hemisphere. When considering the topography of the individual FC findings, the following regions most frequently involved (and listed in descending order of occurrence) were parieto-temporal, frontal-prefrontal and occipito-parietal.

Discussion

To the best of the author's knowledge, this is the first study reporting dynamic changes in brain FC associated with anomalous interactions between monozygotic twins. Specifically, we observed statistically significant changes in receiver FC when the event related FC measure was determined using the sender viewing times. As such Hypothesis 1 was confirmed.

The findings are thus consistent with past research that reported correlated biometric or brain activity between pairs of individuals that share a close emotional relationship. Of particular note is the fMRI study reporting anomalous interactions in a set of monozygotic twins [10]. Aside from Duane & Behrendt [4], these were the only studies that reported biometric or brain activity changes suggesting anomalous interactions between identical twins.

While there were more statistically significant cases when Senders were viewing personal images compared to general images, the small numbers made this difference statistically insignificant. Thus, hypothesis 2 was not confirmed.

While the anomalous interactions between the twins tended to be characterized most frequently by FC increases, a prominent feature of the results was the large intersubject variability. While only approximately 1/3 of the individual findings were associated with statistically significant FC increases or decreases, these FC features exhibited significant inter-individual variability in terms of FC increases or decreases, the topography or regions involved in the FC changes and the timing of the receiver FC changes.

While relatively large individual differences in regional brain activity and FC are commonly observed in cognitive neuroscience brain imaging studies [31], these findings suggest an additional layer of complexity in interpreting individual receiver data based on what the sender is viewing. Specifically, the receiver FC changes are presumed to be associated with the receiver's unconscious subjective responses which are, in turn, presumed to be influenced by the sender's subjective response to the images being presented. In other words, what we observe as Receiver FC changes may be influenced by two successive layers of subjective response. Each of these two layers of subjective responses likely add a significant degree of inter-individual variability. Thus, expecting a consistent relationship between the content of the images as viewed by the Sender and the Receiver FC changes is unrealistic. More generally, if such large inter-individual variability is a common feature of FC changes associated with anomalous interactions, then this suggests that simple pooling or cross-subject averaging is likely to dilute individual effects and yield non-significant findings.

Another factor warranting comment is the relatively strong experimental effect size observed (Cohen's d=0.87). This is a relatively high effect size, especially for studies examining anomalous cognition effects [32]. It is possible that several experimental factors contributed to this high effect size. One factor may be the recruitment method. By limiting recruitment to monozygotic twins, the chance of observing experimental statistically significant effects may have increased. Past research has shown that monozygotic twins tend to report stronger emotional attachment with their twin [33, 34] and a higher prevalence of anomalous shared experiences [1]. when compared to fraternal (dizygotic) twins. Additionally, participants were required to have previously shared an anomalous experience. This may have also contributed

as past studies have shown that a belief in the reality of anomalous cognition effects is associated with a greater likelihood of exhibiting positive findings [35].

Another factor is the choice of methodology used to measure FC changes (SSVEP-ERPC). This methodology has been used to examine FC and FC changes in areas as diverse as the neural correlates of mental rotation [19], creativity [24, 36] and attention deficit hyperactivity disorder [21-23]. Previous research has found this methodology to be especially sensitive to the FC correlates of cognitive processes. These processes are now thought to involve top-down or feedback communication between cortical neural networks and are understood to be mediated by synchronous oscillations in the 10Hz – 20Hz range [37, 38]. As this methodology is only sensitive to the synchronous oscillations or FC occurring at the stimulus frequency of 13Hz, this means that top-down processes are primarily registered, and these may be the ones that play a significant role in processing the anomalous interactions observed.

Finally, the relatively high effect size may, in part, be due to the visual flicker stimulus frequency. This is the fact that both twins were exposed to the same 13Hz stimulus used to elicit the SSVEP. In other words, both stimuli were precisely synchronized with a zero-phase difference. Whilst highly speculative, this factor is based on findings emerging from EEG hyper-scanning studies where positive social interactions between individuals was associated with increased intersubject synchronization of EEG power in various frequency ranges [39]. An intriguing finding suggesting that eliciting interbrain synchronization may enhance positive social interactions was reported by Yang et al [40]. In this study, rat frontal cortex was activated opto-genetically using an implanted light source. The authors report that the effect of optogenetically stimulating two rats at the same frequency is to increase positive social interactions between the rats [40]. This occurs even if the rats exhibit mutual antagonistic behaviour before the optogenetic stimulation. Taking account of the human hyperscanning studies pointing to synchronous brain oscillations increased positive social interactions together with the intriguing findings reported by Yang et al [40], it may be that exposing both the sender and receiver to the same visual flicker stimulus frequency may enhance the strength of the anomalous interaction. The current experimental design cannot determine whether this hypothetical 'interbrain synchrony' effect was present or not. However, future studies will explore the sensitivity of the anomalous interaction FC effects to differences in sender-receiver flicker frequency.

Given the nature of the findings, it is important that this study be independently replicated. Furthermore, any such a replication should faithfully comply with certain key features of the present study. Firstly, it is important to recruit monozygotic twins who report having experienced anomalous interaction and are therefore positively inclined to believe these effects are real. In addition, it is important to use the SSVEP-ERPC methodology with a 13Hz flicker frequency. Given that the FC components observed using the SSVEP-ERPC were primarily a reflection of top-down effects, the specificity of this methodology is considered an important factor contributing to the experimental size effect.

Limitations and Future Directions

Finally, this study suffered from several limitations. Although 10 participants make this one of the larger studies its kind, the sample size is too small to reliably identify any consistent features in the topography or timing of the FC components. It is therefore recommended that future studies recruit a larger number of participants. Another important limitation was the relatively small number of scalp recording sites. The small number of electrodes severely reduced the spatial resolution of the findings. Subsequently, this prevented the use of inverse mapping techniques that would enhance the ability to accurately identity which cortical areas

are contributing to the FC changes. Future studies could employ 64 electrode headsets, thus greatly improving spatial resolution. Another limitation stemmed from the use of a 20m cable to ensure that both twins were exposed to the same 13Hz stimulus. This meant that twins could not be spatially separated by more than 20m. While this is not a serious limitation, it hinders the ability to explore the effect of spatial separation on the anomalous interactions. Subsequently, recording systems capable of precisely synchronizing the flicker stimulus between twins without the necessity of using a cable would allow spatial separation to be explored.

Conclusion Results from this study support the presence of anomalous interactions between sensorily isolated monozygotic twins. Specifically, statistically significant changes were observed in Receiver FC when trials were synchronized to the Sender image. The novel findings of this study, in conjunction with the unique application of methodology, necessitates future replication and further research.

CRediT authorship contribution statement

Richard Silberstein: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft.

Felicity Bigelow: Investigation, Methodology, Project Administration, Data curation, Writing – review & editing.

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