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BASIC RESEARCH ARTICLE

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Posttraumatic growth EEG neuromarkers: translational neural comparisons with resilience and PTSD in trauma-exposed healthy adults

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ABSTRACT

Background: Supporting wellbeing beyond symptom reduction is necessary in trauma care. Research suggests increased posttraumatic growth (PTG) may promote wellbeing more effectively than posttraumatic stress disorder (PTSD) symptom reduction alone. Understanding neurobiological mechanisms of PTG would support PTG intervention development. However, most PTG research to-date has been cross-sectional data self-reported through surveys or interviews.

Objective: Neural evidence of PTG and its coexistence with resilience and PTSD is limited. To advance neural PTG literature and contribute translational neuroscientific knowledge necessary to develop future objectively measurable neural-based PTG interventions.

Method: Alpha frequency EEG and validated psychological inventories measuring PTG, resilience, and PTSD symptoms were collected from 30 trauma-exposed healthy adults amidst the COVID-19 pandemic. EEG data were collected using custom MNE-Python software, and a wireless OpenBCI 16-channel dry electrode EEG headset. Psychological inventory scores were analysed in SPSS Statistics and used to categorise the EEG data. Power spectral density analyses, *t*-tests and ANOVAs were conducted within EEGLab to identify brain activity differentiating high and low PTG, resilience, and PTSD symptoms.

Results: Higher PTG was significantly differentiated from low PTG by higher alpha power in the left centro-temporal brain area around EEG electrode C3. A trend differentiating high PTG from PTSD was also indicated in this same location. Whole-scalp spectral topographies revealed alpha power EEG correlates of PTG, resilience and PTSD symptoms shared limited, but potentially meaningful similarities.

Conclusion: This research provides the first comparative neural topographies of PTG, resilience and PTSD symptoms in the known literature. Results provide objective neural evidence supporting existing theory depicting PTG, resilience and PTSD as independent, yet co-occurring constructs. PTG neuromarker alpha C3 significantly delineated high from low PTG and warrants further investigation for potential clinical application. Findings provide foundation for future neural-based interventions and research for enhancing PTG in trauma-exposed individuals.

Neuromarcadores EEG de crecimiento postraumático: comparaciones neuronales traslacionales con resiliencia y trastorno de estrés postraumático en adultos sanos expuestos a traumatismos

Antecedentes: Apoyar el bienestar más allá de la reducción de los síntomas es necesario en el cuidado del trauma. Las investigaciones sugieren que un mayor crecimiento postraumático (PTG por sus siglas en inglés) puede promover el bienestar de manera más efectiva que la sola reducción de síntomas del trastorno de estrés postraumático (TEPT). Comprender los mecanismos neurobiológicos del PTG apoyaría el desarrollo de intervenciones de PTG. Sin embargo, la mayoría de las investigaciones sobre PTG hasta la fecha han consistido en datos transversales autoinformados a través de encuestas o entrevistas. La evidencia neuronal objetiva del PTG y su coexistencia con resiliencia y TEPT es limitada.

Objetivo: Hacer avanzar la literatura sobre PTG neuronal y contribuir con el conocimiento neurocientífico traslacional necesario para desarrollar futuras intervenciones de PTG de base neuronal objetivamente medibles.

Método: Se recopilaron EEG de frecuencia alfa e inventarios psicológicos validados que miden PTG, resiliencia y síntomas de TEPT de 30 adultos sanos expuestos a trauma en medio de la pandemia de COVID-19. Los datos de EEG se recopilaron utilizando el software MNE-Python

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PALABRAS CLAVE

Alfa; afrontamiento; electroencefalograma (EEG); crecimiento postraumático (PTG); trastorno de estrés postraumático (TEPT); resiliencia; circuito neuronal

关键词

alpha; 应对; 脑电图(EEG); 创伤后成长 (PTG); 创伤后应激障碍 (PTSD); 心理韧性; 神经回路

HIGHLIGHTS

- Objective translational study designed to increase neural understanding of posttraumatic growth (PTG) and provide a basis for future neural-based interventions to enhance PTG.
- Results provide neural evidence of PTG as an independent construct that coexists, and shares limited neural relatedness with resilience and PTSD symptoms.
- Increased PTG was significantly related to higher alpha power in the left centro-temporal brain area around EEG electrode C3: This finding warrants further investigation for potential clinical application.

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personalizado y un Dispositivo cefálico de EEG inalámbrico de electrodo seco OpenBCI de 16 canales. Las puntuaciones del inventario psicológico se analizaron en SPSS Statistics y se utilizaron para categorizar los datos del EEG. Se realizaron análisis de densidad espectral de potencia, pruebas *t* y ANOVA en EEGLab para identificar la actividad cerebral que diferenciara los síntomas de PTG alto y bajo, resiliencia y trastorno de estrés postraumático.
Resultados: El PTG alto se diferenció significativamente del PTG bajo por un mayor poder alfa en el área centro-temporal izquierdo del cerebro alrededor del electrodo C3 del EEG. En este mismo lugar también se indicó una tendencia diferenciadora del PTG alto con el TEPT. Las topografías espectrales de todo el cuero cabelludo revelaron correlaciones de EEG de potencia alfa con PTG, la resiliencia y los síntomas de TEPT compartían similitudes limitadas, pero potencialmente significativas.
Conclusión: Esta investigación proporciona las primeras topografías neuronales comparativas de PTG, resiliencia y síntomas de TEPT en la literatura conocida. Los resultados proporcionan evidencia neuronal objetiva que respalda la teoría existente que describe el PTG, la resiliencia y el TEPT como constructos independientes pero coexistentes. El neuromarcador alfa C3 de PTG distingue significativamente el PTG alto del bajo y justifica una mayor investigación para una posible aplicación clínica. Los hallazgos proporcionan la base para futuras intervenciones e investigaciones de base neuronal para mejorar el PTG en personas expuestas a traumas.

创伤后成长EEG神经标志物：创伤暴露的健康成人的心理韧性和PTSD的转化神经比较

背景：在创伤护理中，除了减轻症状之外，还需要支持健康。研究表明，增加创伤后成长（PTG）可能比单独减少创伤后应激障碍（PTSD）症状更有效地促进健康。了解PTG 的神经生物学机制将支持 PTG 干预的发展。然而，迄今为止，大多数 PTG 研究都是通过调查或访谈自我报告的横截面数据。PTG 及其与心理韧性和 PTSD 共存的客观神经证据有限。
目的：推进神经 PTG 文献的发展，并贡献开发未来客观可测量的基于神经的 PTG 干预措施所需的转化神经科学知识。
方法：从 30 名在 COVID-19 疫情期间创伤暴露的健康成人中收集了 Alpha 频率EEG和经过验证的心理量表，测量 PTG、心理韧性和 PTSD 症状。使用定制的 MNE-Python 软件和无线 OpenBCI 16 通道干电极EEG耳机收集EEG数据。在 SPSS 统计中分析心理量表分数，并用于对EEG数据进行分类。 在 EEGLab 内进行功率谱密度分析、t 检验和方差分析，以识别不同的高和低 PTG、心理韧性和 PTSD 症状的大脑活动。
结果：较高的 PTG 与低 PTG 的显著差异在于 EEG 电极 C3 周围左侧中央颞叶脑区较高的 α 功率。 在同一位置还表明了不同的高 PTG 和 PTSD 的趋势。 全头皮光谱地形图显示，α 功率EEG与 PTG、心理韧性和 PTSD 症状的相关性有限，但具有潜在意义的相似性。
结论：本研究首次提供了已知文献中 PTG、心理韧性和 PTSD 症状的神经拓扑图比较。结果提供了客观的神经证据，支持现有的理论，将 PTG、心理韧性和 PTSD 描述为独立但同时发生的结构。PTG 神经标志物 α C3 显著描绘了高 PTG 和低 PTG，值得进一步研究潜在临床应用。研究结果为未来基于神经的干预措施和增强创伤暴露个体 PTG 的研究奠定了基础。

Due to the strong need to relieve suffering, negative trauma outcomes receive the greatest focus in trauma research and clinical practice. However, understanding how individuals respond to trauma in psychologically healthy ways is also of considerable clinical importance. Recent trauma research indicates that higher levels of posttraumatic growth (PTG) have been found to promote wellbeing more effectively than lowering symptoms of posttraumatic stress disorder (PTSD) (Hamby et al., 2021). Therefore, finding ways to enhance PTG (advantageous psychological transformations following trauma) is vital in trauma recovery.

Research examining PTG has steadily increased in the last three decades since its inception (Kou et al., 2021). However, efforts to understand PTG thus far have predominantly been based on self-reported data collected through surveys and interviews. Few studies have objectively examined the neuromarkers of PTG, and as a result, neural understanding of PTG remains limited (Dell'Osso et al., 2023).

Furthermore, PTG is known to co-occur with PTSD (Leiva-Bianchi & Araneda, 2014; Shakespeare-Finch & Lurie-Beck, 2014; Taku et al., 2021; Tedeschi et al., 2018), and resilience (Chen et al., 2022) in varying combinations (Tedeschi et al., 2018). This co-occurrence serves to further complicate the identification of PTG neuromarkers. For example, a meta-analysis suggested PTG and PTSD share a curvilinear relationship, whereby PTG and PTSD increase together only until a certain point, at which PTG begins to drop off as PTSD symptoms increase (Shakespeare-Finch & Lurie-Beck, 2014). Additionally, resilience has been found to positively correlate with and partially mediate the development of PTG (Li et al., 2020), as well as moderate the relationship between PTG

and PTSD (Ying et al., 2016). Despite this known co-occurrence, to-date there has been no neural examination of PTG, resilience, and PTSD together in the same study. Given the complex interconnectedness, the inclusion of resilience and PTSD measures in the neural examination of PTG is warranted, both for theory development and the development of future PTG neural interventions.

1. Current status and challenges of neural PTG research

While neurobiological studies are emerging rapidly in trauma resilience (Roeckner et al., 2021) and PTSD (Al Jowf et al., 2023; Chen et al., 2021; Nicholson et al., 2022; Paganin & Signorini, 2023), the neural understanding of PTG remains limited (Dell'Osso et al., 2023). Only four studies define the field examining neural circuitry in PTG (Anders et al., 2015; Fujisawa et al., 2015; Glazebrook et al., 2023; Rabe et al., 2006). An early co-mingled eyes open and closed EEG study of 82 motor vehicle accident survivors with (n = 45) and without PTSD (n = 37), who were shown trauma-related pictures, found left fronto-central activation corresponding with higher PTG scores (Rabe et al., 2006). An eyes closed resting functional magnetic resonance imaging (fMRI) examination of PTG and basal whole-brain functional connectivity in 33 healthy young adults before and after an earthquake, also found positive associations between PTG and left-brain activity, especially in the rostral prefrontal cortex and superior parietal lobule associated with the central executive network (Fujisawa et al., 2015). Magnetoencephalogram (MEG) research examining PTG in the task-free, eyes open resting-state brain activity of 299 war veterans, with (n = 106) and without PTSD (n = 193), observed global synchronous neural interactions (i.e. activity preventing simultaneous coordinated activity across brain networks) significantly decreased as PTG scores increased, especially in the left medial prefrontal cortex, but only for individuals without PTSD (Anders et al., 2015). Anders et al. (2015) posited that this de-correlating synchronised left-brain activity may free up the neural space to enable PTG, while the continued presence of synchronised brain network activity may be associated with maintaining PTSD. Despite the many and varied methodological differences between these neural PTG studies, all found PTG was identifiable in human brain activity. Furthermore, these studies found that PTG was predominantly identifiable in left lateralised brain activity (Anders et al., 2015; Fujisawa et al., 2015; Rabe et al., 2006).

Most recently, an EEG study used machine learning to determine whether brain activity patterns could be used to classify 67 trauma-exposed healthy individuals as reporting high versus low PTG (Glazebrook et al., 2023). Participants were measured in task-free eyes closed, and picture-viewing task conditions. Results demonstrated that patterns of EEG alpha power could be used to predict with high accuracy which individuals reported high versus low PTG (Glazebrook et al., 2023). Both that study (Glazebrook et al., 2023) and the earlier EEG-measured PTG study (Rabe et al., 2006) found PTG was specifically identifiable in alpha frequency band power patterns of brain activity.

1.1. Current study

Given the demonstrated usefulness of EEG alpha power in identifying PTG, EEG was selected as the ideal method for undertaking the current PTG neural study. During EEG studies, measurements of brain activities are collected with eyes open or eyes closed. To approximate brain activity, estimates of power spectral density (PSD) are calculated from data collected in each different EEG frequency band at different topographical locations across the scalp. PSD is a data reduction technique used to transform the brain activity, collected as an EEG channel-by-time matrix, into a single array of numbers (one per EEG channel) pared with each topographical location. Each number represents the EEG power, as a measure of the amount of brain activity at that location. By measuring the EEG alpha power, the current study sought to further examine the previous findings of significant left lateralised brain activity in individuals with higher PTG. The current study also sought to compare patterns of EEG power present in high and low PTG compared to resilience and PTSD symptoms.

Furthermore, all previous PTG neural research was conducted with complex and expensive laboratory-based EEG, MEG and fMRI equipment, the likes of which are rarely seen outside of universities and large medical centres. To ensure the translational value of the research, this study used affordable, portable EEG equipment. This decision was in accord with the European Framework for Action on Mental Health 2021–2025, which champions for broader population access to new interventions and technology-based enhancements (WHO Regional Office for Europe, 2022). Previous research has demonstrated the effectiveness of using such affordable portable EEG technology in wellbeing research (Cannard et al., 2021).

By examining the neural representation of high versus low PTG, compared to resilience and PTSD, the current study sought to identify neuromarkers that

may inform the development of future neural-based PTG interventions. Based on existing literature, it was hypothesised that left lateralised neuromarkers differentiating high from low PTG would be identified using alpha power. It was also hypothesised, that despite (or perhaps because of) their varying coexistences, the distinctly different, independent constructs of PTG, resilience and PTSD would produce distinctly different neural patterns.

2. Method

2.1. Participants

Thirty participants were recruited to the study. Participants included 18 females, and 12 males (intersex $n = 0$), aged 18–63 years ($M = 37.70$; $SD = 10.76$), who were predominantly right-handed ($n = 28$; left-handed $n = 1$; ambidextrous $n = 1$). Participants were screened as part of the recruitment process to include healthy individuals who had not suffered a brain injury, did not have a history of neurological disorders, did not have a current or past schizophrenic, bipolar, or psychotic disorder, and were not currently under psychological or psychiatric care receiving treatment for a clinically diagnosed psychological disorder.

When asked to describe traumatic experiences, participants who elected to disclose details reported: Life threatening/serious illness or accident $n = 8$; Physical and/or psychological abuse $n = 6$; Relationship breakdown $n = 5$; Death of someone close $n = 4$; Suicide attempt by someone close $n = 2$; Sexual assault $n = 1$; and Traumatic childbirth $n = 1$. Three participants reported multiple trauma types. In addition, data collection took place amidst substantial community disruption, one year after COVID19 was declared a pandemic. Therefore, in addition to the person-specific traumas reported, all participants ($n = 30$) were exposed to unprecedented, ongoing community trauma. When asked to rate how overwhelming the most impactful traumatic circumstance was, on a scale of 1- not at all overwhelming, to 10- extremely overwhelming, participants scored a mean of 8.63 ($SD = 1.01$; range = 7-10).

3. Materials

3.1. Electroencephalogram (EEG)

EEG was used to measure the electrical activity of the brain within recognised frequency bands – delta (1-4 Hertz (Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (30-45 Hz) (Reaves et al., 2021). Data were collected using customised open-source software built in MNE-Python (van der Meer, 2019), and a wireless OpenBCI Ultracortex MarkIV open-source EEG headset and 16-channel Cyton Daisy biosensing board. The sampling rate was 125 samples per second. Brain signals were collected via 16 dry comb scalp surface electrodes, positioned at FP1, FP2, F3, F4, F7, F8, C3, C4, T7, T8, P7, P8, P3, P4, O1, O2, in accordance with the international 10–20 system (Jasper, 1958). Ground electrode was located at the right earlobe, and reference at the left earlobe.

3.2. Online questionnaire

Validated, self-administered inventories were used to measure PTG, resilience, and PTSD. These inventories and basic demographic questions were presented to participants in an online questionnaire created in QualtricsXM v2021 survey software.

Posttraumatic Growth Inventory – Expanded (PTGI-X). The PTGI-X (Tedeschi et al., 2017) measures positive psychological growth derived from highly challenging life situations. The 25-item inventory uses a six-point rating scale ranging from 0 (I did not experience this change) to 5 (to a very great degree) to measure PTG across five factors, including changes in personal strength, relationships, perception of new possibilities, appreciation of life, and spiritual, existential, or philosophical changes. Potential scores range from 0-125. Higher scores are suggestive of higher levels of PTG. The PTGI-X has been validated with strong reliability across different cultures ($\alpha = .93$ to .97; Taku et al., 2021; Tedeschi et al., 2017). Cronbach's alpha for this study was $\alpha = .96$.

Posttraumatic Stress Disorder Checklist for Diagnostic and Statistical Manual of Mental Disorders, fifth edition (PCL-5). The PCL-5 (Weathers et al., 2013) measures 20 DSM-5 symptoms of PTSD. The 20-item checklist uses a five-point rating scale from 0 (not at all) to 4 (extremely), with potential scores ranging from 0-80. Scores of 33–34 and above are indicative of probable PTSD, requiring further assessment (Murphy et al., 2017; Weathers et al., 2013). Strong internal validity ($\alpha = .94$) and test-retest reliability ($r = .82$) have previously been found (Blevins et al., 2015). Cronbach's alpha for this study was $\alpha = .96$.

Brief Resiliency Scale (BRS). The BRS (Smith et al., 2008) measures the self-perceived ability to bounce back from stressful circumstances, using a five-point rating scale ranging from 1-strongly disagree to 5-strongly agree. The 6-item scale produces total scores from 1 to 5, indicative of low resilience: 1.00-2.99, normal resilience 3.00-4.30, high resilience 4.31-5.00 (Smith et al., 2008). The BRS has been validated as a unitary construct with good internal reliability ($\alpha = .80$ to .91; Smith et al., 2008). Cronbach's alpha for this study was $\alpha = .95$.

3.3. Procedure

Ethical approval was granted prior to commencement by the University Human Research Ethics Committee

under Approval no. 2000000067. The completion of online questionnaires was counterbalanced so that half of the participants completed the questionnaire prior to the EEG measurement, and half after. Informed written consent was gained at the commencement of the questionnaire. Participants completed the questionnaire either on their own device or a device provided by the researcher.

Following recruitment, participants were scheduled to an individual, in-person testing appointment in a quiet location with limited electrical interference. Informed written consent was gained from participants prior to participating in the EEG measurement. After fitting the EEG headset, signal checks were performed using the OpenBCI Graphical User Interface (v5.0.1, OpenBCI, 2020). Adjustments were made to lower any electrical impedance prior to data collection. During EEG recording, participants were seated with a naturalistic outlook (i.e. trees and nature). They were instructed to look straight ahead with eyes open, thinking of nothing in particular, allowing their minds to wander, blinking as normal, and remaining as still as possible while 3 min of eyes open EEG was collected. Following a short 30 s rest period, participants were asked to close their eyes and remain as still as possible while 3 min of eyes closed EEG was collected.

3.4. Statistical analysis

Analysis of the psychological measures was performed in Statistical Package for the Social Sciences (SPSSv28). Parametric and non-parametric testing was performed and compared as a means of assumption testing in SPSS. As both tests produced highly similar results, parametric results were reported (Field, 2018) for the psychological measures analyses. EEG data analysis and visualisation was performed in EEGLab v2021.1 (Delorme & Makeig, 2004) in MATLAB scientific statistical software R2021b (MathWorks Inc., USA). Scores from the psychological testing were used to categorise the EEG for data analysis. As the PTGI does not specify cut-off scores, high, moderate, and low PTG was decided by dividing participant scores into thirds. Precedence for this approach was established by previous research (Glazebrook et al., 2023). Categorical ANOVA and *t* test analyses were selected over regression, as this study aimed to identify and visualise neuromarkers differentiating high from low PTG, and PTG from resilience, and PTSD.

3.5. EEG pre-processing

In the pre-processing stage, the raw EEG data were visually inspected to identify bad data segments and bad channels. Bad data segments were removed to reduce effects of sudden motion and muscle artefacts. If an EEG channel had consistently bad signal, it was removed. After segment and channel removal, the EEG was high-pass filtered at 1 Hz to remove drifts, and a 50 Hz notch filter was applied to reduce power line artefacts. Independent Component Analysis using Preconditioned ICA for Real Data (PICARD) (Ablin et al., 2018) was performed to de-mix the EEG data into a set of components. Datasets recorded for the same individual were concatenated to improve ICA quality. Components with an 80% probability of being eye movements were automatically labelled for rejection using ICLabel (Pion-Tonachini et al., 2019). The ICA labelling was visually inspected, and any additional artefacts identified were labelled for rejection. After rejection, components were re-mixed into channel EEG data. Finally, spherical interpolation was used to replace any removed channels in the initial pre-processing stage. Channel data were then re-referenced to an average derived from all measurement channels in the montage.

3.6. Spectral analysis

Precomputations for EEG power analysis were undertaken within the EEGlab graphical user interface (GUI), using Fast Fourier Transformation (FFT) to calculate Power Spectral Density estimates (PSD). Power spectrum estimation was undertaken with the multitaper method using discrete prolate spheroidal sequences (DPSS) windows (Thomson, 1982). As the data was continuous, window size was set to 1 s epochs, overlapping by 50%. To assess group differences in absolute alpha power between the high to low groups for each psychological measure (PTG, resilience, and PTSD), one-way between-subject ANOVAs were conducted. Unpaired *t*-tests were undertaken to assess the group differences between PTG, resilience, and PTSD. Holms-bonferroni correction for multiple comparisons was applied to increase the strength of the analysis by controlling for Type I (false positive) errors. All analyses were performed with both eyes open and eyes closed EEG recordings.

Absolute alpha power was selected as the primary neural measure in the current study as it enabled direct comparisons and straightforward interpretation of differences between groups and conditions in the current study and broader literature. Absolute alpha also retains potentially relevant individual differences in alpha power and avoids issues inherent to normalisation. However, accuracy in brain analysis may be enhanced by also considering relative alpha PSD, that is, the ratio of absolute alpha EEG frequency power to total spectrum power across all frequencies. Relative alpha power offers the advantage of minimising inter-individual differences caused by interference from the EEG headset and different skull thicknesses. However, as a normalised ratio measure, relative alpha

power is impacted by neural activity in other frequencies. As the PSD in other frequency bands increases, the PSD ratio of relative alpha is decreased, and vice versa. Despite its caveats, relative alpha power may be used to facilitate validation cross checking of the absolute alpha main analysis.

Accordingly, as an additional means of exploring the data and validating the results, ad hoc supplementary PSD analyses were undertaken using relative alpha power. Code calculating relative alpha power for each participant was developed and read into EEGlab. The methods described above for conducting the absolute alpha PSD analysis in the EEGlab GUI were then replicated to produce a comparative supplementary set of PSD results for relative alpha power.

4. Results

4.1. Psychological measures

Table 1 displays participant scores for posttraumatic growth (PTGI-X), resilience (BRS), and symptoms of PTSD (PCL-5). PTG means and standard deviations are similar to those reported by other studies using the PTGI-X (e.g. David et al., 2021; Miller et al., 2020), indicating that PTG in the study sample was representative of the general non-clinical population. The full range of resilience was represented, with 14 participants (47%) reporting normal levels of resilience, 9 (30%) reporting low resilience and 7 (23%) reporting high resilience. Almost one-third of participants ($n = 8$) returned PCL-5 scores of above the suggested diagnostic cut-off of 33, indicating a potential for PTSD.

A moderate negative correlation was evident between PTSD symptoms and resilience, $r(28) = -.543$, $p = .002$. Quadratic regression indicated that 41% of the variation in PTSD was explained by resilience, $F(2,27) = 9.23$, $p < .001$. PTG is often found to have a strong linear and even stronger curvilinear relationship with PTSD (Shakespeare-Finch & Lurie-Beck, 2014). However, in this sample, PTG was not significantly linearly corelated with either resilience, $r(28) = .12$, $p = .522$, or PTSD, $r(28) = .02$, $p = .919$. Quadratic regression revealed there were also no significant curvilinear relationships between PTG and resilience, $F(2,27) = .35$, $p = .710$, or PTSD, $F(2,27) = .243$, $p < .786$ in this sample.

Table 1. Means, standard deviations and range for psychological measures.

Scale	*M*	*SD*	Range
PTGI-X: Posttraumatic Growth	*69.40*	*30.17*	*3–113*
Relating to Others	2.66	1.29	0–5
New Possibilities	2.91	1.24	0–5
Personal Strength	3.15	1.47	0–5
Spiritual, Existential, Philosophical	2.32	1.58	0–5
Appreciation of Life	3.23	1.15	1–5
BRS: Resilience	*3.43*	*1.01*	*1–5*
PCL-5: PTSD Symptoms	*23.47*	*18.86*	*0–61*
Criteria B: Intrusion	6.43	5.65	0–19
Criteria C: Avoidance	2.40	2.25	0–8
Criteria D: Neg. Cognitions & Mood	8.40	7.75	0–24
Criteria E: Neg. Arousal & Reactivity	6.17	5.30	0–16

Note. PTGI-X = Posttraumatic Growth Inventory – Expanded; BRS = Brief Resiliency Scale; PCL-5 = Posttraumatic Stress Disorder Checklist for DSM-5.

4.2. EEG spectral analysis

Alpha frequency power plots revealed two potential outliers in the eyes closed EEG data. Subsequent SPSS box–whisker analysis of the average power of all channels at 10 Hz identified these two participants as extreme outliers based on an interquartile range of 3. These participants had abnormally low voltage alpha. This low voltage alpha phenotype has been observed in 3-13% of the healthy population (for summary see Bazanova & Vernon, 2014). To avoid skewing the results, these two participants were excluded from further analysis.

As expected in a healthy population, all groups displayed the highly replicated pattern of alpha suppression in eyes open compared to eyes closed (Bazanova & Vernon, 2014), and an alpha peak frequency of around 10 Hz (Angelakis et al., 2004). These findings indicate basic neural function in the analysed sample was reflective of the general population.

Spectral topographies in Figure 1A depict the average total strength of alpha power over time, at each electrode, for the high, medium, and low groups of each psychological measure. Observably different alpha power patterns were evident for PTG, compared to resilience and PTSD. Despite substantial individual differences within groups, Figure 1B demonstrated a statistically significant difference in alpha frequency power between high and low PTG in the left centro-temporal brain area surrounding electrode C3 in the eyes open condition, and to a lesser degree the eyes closed condition. Alpha power increased at C3 as PTG increased. Furthermore, as demonstrated in Figure 1C, the analysis also revealed a trend denoting higher eyes open alpha power in high PTG compared to probable PTSD. There were no other trends significant points of difference in mean alpha power across the electrodes between any other specific levels of PTG, resilience, and PTSD.

Relative alpha power results, presented in Supplement A, provide complementary information regarding alpha as it relates to PTG, resilience and PTSD. In this supplementary figure, the results are presented in the same format as Figure 1, however instead of absolute alpha power, relative power topographies are displayed. Although no significant results were found, the relative alpha power results derived from the supplementary analysis demonstrate a similar pattern of higher alpha power at C3 in the high PTG group, compared to the low PTG and probable PTSD groups. Therefore, the

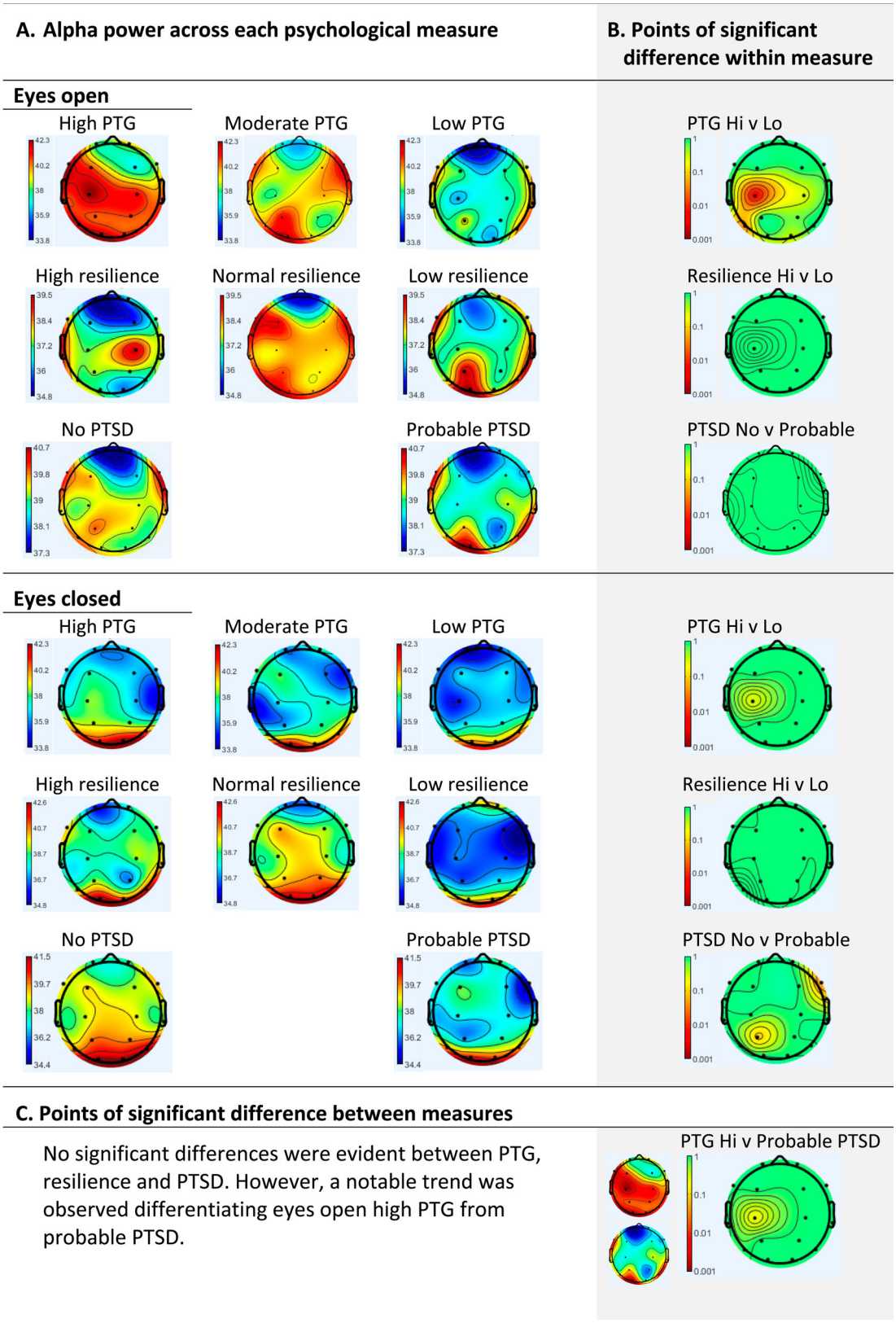

Figure 1. Average Absolute Alpha 8-12 Hz Frequency Band Group EEG Scalp Topographies of PTG, Resilience and Probable PTSD. A. Alpha power across each psychological measure. B. Points of significant difference within measure. C. Points of significant difference between measures.

Note: A. EEG scalp topographies depict the group average absolute alpha power at each electrode when all levels of a psychological measure are compared in ANOVA analyses. Colorbars identify high (red) to low (blue) alpha EEG power for each scalp topography. B. ANOVA statistical analysis with Holm-Bonferroni correction for multiple comparisons revealed points of significant difference in group average absolute alpha power across the levels of each psychological measure. Colorbars identify significance levels from non-significant $p = 1$ (green) to significant $p = <.001$ (red). *C.* T test statistical analyses revealed points of significant difference in group average absolute alpha power between each level of PTG with each level of resilience and PTSD. Colorbar in the left panel identifies high (red) to low (blue) alpha EEG power for each scalp topography. Colorbar in the right panel identifies the significance from non-significant p=1 (green) to significant $p = <.001$ (red).

relative alpha power results provide a level of validation for the main findings of the current study.

5. Discussion and directions for future research

The current study advances the limited literature examining the representation of PTG in healthy human brain activity. It also contributes, for the first time, a neural comparison of PTG with resilience, and PTSD. While existing PTG literature is predominantly built on subjective measures and observations, the current study offers objectively measured neural findings. These objective neural findings may provide a foundation for future neural PTG theory development, objective clinical measures, and neural PTG interventions. Furthermore, this study demonstrates the feasibility of using accessible, portable, dry electrode EEG to effectively measure significant PTG-related differences in alpha power. This is important because it allows effective, highly translational research, and clinical assessments and interventions, to be performed in locations away from the universities or medical centres where the larger, more expensive, neural imaging equipment, including high-density EEG, is generally housed.

In the current study, higher alpha power was significantly positively related to higher PTG in the left centro-temporal brain at electrode C3 with eyes open, and to a lesser extent with eyes closed. This finding offers potential clinical significance warranting further investigation. Discovering a PTG neuromarker in the left brain hemisphere, as hypothesised, replicates previous neural PTG research, suggesting important PTG-related neural processing may occur in left-brain regions (Anders et al., 2015; Fujisawa et al., 2015; Rabe et al., 2006). Also as hypothesised, alpha power was found to identify a neuromarker that significantly differentiated high from low PTG. Finding a neuromarker in alpha frequency also echoes the results of previous EEG-measured PTG research (Glazebrook et al., 2023; Rabe et al., 2006).

Existing neuroscientific literature suggests alpha plays a prominent role in cognitive processing and self-regulation (Bazanova & Vernon, 2014). Alpha power within the sensorimotor cortex, over which C3 is located, is recognised as performing a 'switch' gating role (Micoulaud-Franchi et al., 2021). By directly increasing or decreasing neuronal firing, alpha facilitates switching between excitation/inhibition (lower/higher alpha), resulting in higher/lower stress and arousal (for summary see Micoulaud-Franchi et al., 2021). For example, higher alpha power, such as that observed at C3 in the current task-free study, is associated with a decreased awareness and focus on external stimuli, potentially resulting in lower stress and arousal. By inhibiting undue focus on distracting information from the environment, higher alpha power may enable an advantageous increase in task focus (Jensen & Mazaheri, 2010). The PTG model put forward by Tedeschi et al. (2018) suggests, PTG transformations are generated through an iterative process involving self-analysis, rumination, and emotional self-management. Accordingly, higher alpha power at C3 may create a neurobehavioural and emotional 'rest', that allows focused cognitions, required for PTG to occur.

This functional theory may build on the suggestion by Anders et al. (2015), that decorrelations (higher alpha power) in the medial prefrontal cortex, observed during MEG, may represent the brain releasing neural networks from the hold of sensory input related to trauma processing; thus freeing up neurocognitive space to encode new information that allows PTG to occur. Higher alpha power over the left sensorimotor cortex at C3 may contribute to this unfolding neural theory of PTG. By blocking information with the potential to cause undue neurophysiological and cognitive/behavioural over-arousal, or distraction, higher alpha power at C3, as required, may selectively enable PTG-enhancing self-cognitions to occupy neural space. Healthy trauma-exposed individuals with high PTG may have the neural ability to effectively block information as required, to allow a selective focus, or approach/withdrawal coping, which is advantageous to their psychological wellbeing. A systematic review of PTG suggests that this type of cognitive flexibility in approach and avoidance may enable individuals to at times process trauma and at times avoid thoughts and activities when they are too overwhelming (Henson et al., 2020). Cognitively, it may be posited that the significant difference in alpha power between high and low PTG, may be a neural signature related to the cognitive flexibility required to facilitate the deliberate rumination and emotional distress management outlined in the theoretical model of PTG posited by Tedeschi et al. (2018). Future research may investigate this potential. Neural understanding will continue to unfold as future studies add to the emerging neurobiological picture of PTG.

Alpha power at C3 may also occur as part of a yet-to-be-understood network of PTG activity, coordinating multiple brain areas, including sub-cortical brain layers beyond EEG measurement capabilities. Experimental research is required to investigate whether a causal relationship exists (Siddiqi et al., 2022) between high PTG and higher C3 alpha power and/or associated causal networks.

Furthermore, a trend of higher alpha power differentiating high PTG from probable PTSD was also found around the C3 location. This finding replicates existing neural research demonstrating that PTSD is associated with comparatively lower alpha power (see Nicholson et al., 2023). As discussed, research

suggests this lower alpha power permits an increased focus on external stimuli, which may underpin the cognitive, behavioural and neurophysiological states of increased stress and over-arousal associated with PTSD (Micoulaud-Franchi et al., 2021). A neural intervention that promotes PTG brain activity, but also risks promoting PTSD symptoms would be undesirable. Therefore, from a clinical perspective, higher alpha power at C3 being associated with a tendency for lower PTSD symptoms, makes C3 more desirable for use in PTG interventions.

As hypothesised, distinctly different alpha power patterns were observed in the EEG scalp topographies of PTG, resilience, and probable PTSD. This provides support for existing subjectively-measured literature, indicating PTG is a separate construct, co-occurring independently of resilience and PTSD (Leiva-Bianchi & Araneda, 2014; Taku et al., 2021). There are limited similarities shared across specific levels of the measures that may be potentially meaningful and may indicate related cognitive processes. Future research may examine the potential for related cognitive processing and neural similarities that may connect specific levels of PTG, resilience, and PTSD.

5.1. Strengths and limitations

Several limitations exist in the current study. General caution must be exercised when interpreting group topographies, as notable individual differences were observed. Inter-participant variability is common in brain research due to the varied ways the cortex folds across the human brain in different individuals (Singh et al., 2023). This results in differences in active locations during data collection (Singh et al., 2023). Individual differences in the spectral topographies may also reflect the inherent heterogeneity of the healthy participants in the current study. Heterogeneity is a recognised challenge in correlational neuroimaging research (Cohen, 2022). Alternatively, the individual differences observed between the scalp topographies at each level of PTG may be meaningful. Neural research in PTSD suggests that different subtypes of PTSD results in different patterns of neural activity (Zhang et al., 2021). Accordingly, different levels of the five PTG dimensions listed in Table 1, may result in different patterns of neural activity. Research into the neural representation of each PTGI dimension would shed further light on this prospect.

It should also be noted that while the detection of individual differences may appear to complicate the generalisability of group differences found in neural studies, such individual differences are to be embraced. It is this ability to detect individual differences that makes EEG valuable in biometric identification (Reaves et al., 2021) and future neural-based trauma interventions.

Another limitation of this study is that it relies on low density EEG. While the lower number of electrodes enabled the use of portable wireless dry electrodes, the accompanying reduction of data collection points across the scalp may be considered a disadvantage. In addition, EEG only measures cortical activity. Subcortical network circuitry is beyond detection. Finally, while relationships between PTG and brain activity are presented and discussed, causality cannot be assumed from this correlational study (Siddiqi et al., 2022). Experimental research is required to gain a functional neural understanding of PTG.

The current study used objective neural measures to examine the representation of PTG in healthy human brain activity. Results demonstrate high alpha power in the left centro-temporal brain around electrode C3 was associated with higher PTG, and reduced symptoms of PTSD. This finding provides a strong evidence-based foundation for future experimental research to explore the potential of a causal relationship between high PTG and high alpha at C3. A further strength of the current study is the highly translational findings availed using accessible EEG equipment. The current study contributes comparative PTG, resilience, and PTSD neural profiles to the emerging field of PTG brain research. Understanding the complete trauma picture, rather than separating the 'positive' and 'negative' outcomes is beneficial and necessary for supporting the sustained healthy functioning of individuals, families, and communities. The current study contributes to the development of PTG neural theory. It offers justification for the future development of neural-based PTG interventions and preventions, to enhance the wellbeing of trauma-exposed individuals.

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This article has earned the Center for Open Science badges for Open Data. The data are openly accessible at https://doi.org/10.25912/RDF_1684466012814.

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Ethical statement

Ethical approval for this research was granted by the Queensland University of Technology Human Research Ethics

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data supporting the results of this study are available at: Glazebrook, A.J.; Shakespeare-Finch J., Andrews B., van der Meer, J. (2023). Posttraumatic growth neural comparisons with resilience and PTSD in healthy adults. Queensland University of Technology. (Dataset) https://doi.org/10.25912/RDF_1684466012814.

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