Reduced Fast Periodic Visual Stimulation Oddball Responses to Threatening Faces Associated with Anxiety

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Abstract

Facial expression processing is crucial for social communication and survival, with anxiety disorders often linked to alterations in attentional biases toward threat-related stimuli. While previous studies using event-related potentials (ERPs) have yielded conflicting findings regarding threat sensitivity in anxiety, Fast Periodic Visual Stimulation (FPVS) offers a high signal-to-noise, implicit alternative for assessing emotion processing. This study utilized FPVS to investigate neural responses to facial expressions in individuals with anxiety compared to healthy controls. Forty-one adults participated, with 17 classified into the anxiety group based on self-reported diagnosis or PROMIS Anxiety scores. EEG responses were recorded while participants viewed sequences of neutral faces interspersed with emotional oddball expressions (angry, fearful, happy, and sad). Results revealed robust individual- and group-level neural responses, with significantly reduced summed baseline-corrected amplitudes (BCA) in central-parietal regions for angry and happy faces in the anxiety group. These findings suggest that anxious individuals exhibit attenuated discrimination of emotional expressions, particularly in higher-order processing regions, which may reflect cognitive avoidance of threat or general disengagement from emotional stimuli. The study highlights the potential of FPVS as a clinically relevant tool for objectively assessing emotion processing in anxiety and related disorders.

1. Introduction

The rapid and accurate processing of facial expressions is fundamental to human social interaction, as it enables the detection of emotional cues that are critical for survival. From an evolutionary standpoint, the ability to swiftly identify and differentiate facial expressions, particularly those signaling potential threats such as anger or fear, is vital for adaptive behavior (Schettino, et al., 2020). Humans have evolved complex neural systems to categorize facial expressions efficiently, facilitating both rapid visual discrimination and the generalization of emotional cues across different facial identities (Lau & Dzhelyova, 2020).

Individuals with anxiety disorders often exhibit heightened sensitivity to threat-related stimuli, leading to an exaggerated attentional bias toward such cues. This bias is believed to play a significant role in the development and maintenance of anxiety disorders (Bar-Haim, et al., 2005). Supporting this, studies utilizing electroencephalography (EEG) and event-related

potentials (ERPs) have demonstrated enhanced neural responses to threatening faces in anxious individuals. Specifically, anxiety has been associated with increased amplitudes in early ERP components such as the P1, N170, and P200, reflecting heightened early-stage processing of threat-related stimuli (Bar-Haim, et al., 2005) (Chilver, et al., 2022) (Zhao, et al., 2020) (Zhang, et al., 2018). Additionally, augmented late positive potential (LPP) responses have been observed, suggesting sustained attention to emotional stimuli (Schwab & Schienle, 2017) (Moser, et al., 2008).

However, not all studies consistently report these findings. Some research indicates reduced ERP amplitudes in both early and late processing stages among anxious individuals. For example, Frenkel and Bar-Haim (2011) found that early ERP components, such as the P1, P2, and early posterior negativity (EPN), did not significantly differ between anxious and non-anxious groups. Moreover, they observed reduced LPP amplitudes in response to fearful versus neutral stimuli in individuals with anxiety. Steinweg et al. (2020) reported diminished discrimination of fearful faces during both early (EPN) and late (LPP) components. Furthermore, although Holmes et al. (2008) observed an enhanced early P1 response to fearful faces in individuals with high trait anxiety, this was followed by reduced amplitudes in subsequent ERP components. These mixed results may stem from variations in experimental paradigms, task demands, and analytical approaches (Steinweg, et al., 2020).

Fast Periodic Visual Stimulation (FPVS) paradigms have recently emerged as a promising alternative to traditional ERP methods for investigating facial expression processing. FPVS leverages frequency-tagged stimuli to elicit steady-state visual evoked potentials (SSVEPs), providing an objective, high signal-to-noise ratio (SNR) measure of neural discrimination at pre-defined oddball frequencies (Rossion, 2014) (De Rosa, et al., 2022) (Norcia, et al., 2015) (Retter, et al., 2021).

FPVS offers distinct advantages over traditional ERP techniques, including higher sensitivity, greater objectivity, and the ability to capture the complete neural response spectrum, encompassing both low-level sensory processing and higher-order cognitive functions (Norcia, et al., 2015) (Rossion, 2014) (Kastner-Dorn, et al., 2018) (Keil, et al., 2011). Notably, FPVS can probe implicit facial processing and has been shown to discriminate facial identity and emotion at a conceptual level, as evidenced by reduced or absent responses to inverted faces (Coll, et al., 2019) (Dzhelyova, et al., 2017). Prior studies employing FPVS have demonstrated robust neural responses to emotional expressions such as fear, disgust, and happiness, with distinct activation patterns over occipito-temporal regions (Dzhelyova, et al., 2017).

Despite these advances, FPVS has not yet been applied to investigate differences in facial expression processing between clinical populations, such as individuals with anxiety, and healthy controls. The current study aims to fill this gap by examining neural reactivity to emotional facial expressions in both groups using the FPVS paradigm. This approach holds the potential to uncover novel insights into emotion processing deficits in anxiety disorders, contributing to a deeper understanding of their underlying neurobiological mechanisms. Furthermore, due to its robustness and efficiency—with interpretable data at the individual level and short recording times—FPVS shows promise as a practical tool for clinical assessment and screening (Milton, et al., 2020).

2. Methods

2.1 Participants

Forty-one adults (ages 18-28, mean age = 20.8, 21 females) were recruited from the Mississippi State University student population. Ethical approval was obtained from the Mississippi State University Institutional Review Board, and all participants provided written informed consent. Participation was voluntary, and individuals could withdraw at any time. Data from three participants were excluded due to technical issues—two due to EEG recording failures and one due to excessive noise—resulting in a final sample of 38 participants. Participants completed a demographic questionnaire, including self-reported anxiety diagnoses after which the PROMIS Anxiety short form (LEVEL 2- Anxiety-Adult PROMIS Emotional Distress-Anxiety-Short Form) was administered. Participants were classified into the anxiety group based on either a self-reported anxiety diagnosis (n=13) or a PROMIS t-score exceeding 60 (n=4). This classification yielded an anxiety group of 17 individuals (10 females, mean t-score = 60.7) and a healthy control group of 21 participants (11 females, mean t-score = 50.2). All participants had normal or corrected-to-normal vision and hearing.

2.2 Stimuli

Facial stimuli were selected from the validated FACES database (Ebner, et al., 2010), which includes images from 171 individuals aged 19 to 80 (85 females). Each individual is depicted in two images per facial expression, covering six emotional expressions. In this study, five expressions were used: neutral, angry, fearful, sad, and happy. The original 819 x 1,024-pixel images were resized to 158 x 197 pixels at 96 dpi. The stimuli subtended a visual angle of 5° x 6.25° (width x height) and were displayed on a 24-inch monitor with a 60 Hz refresh rate.

2.3 Procedure

Participants were positioned 80 cm from the monitor. During the FPVS paradigm, facial stimuli were presented for 83 ms, followed by an 83 ms blank interval before the next image appeared. Stimuli were displayed in sequences of five images, with the first four being base images and every fifth image serving as an oddball stimulus. This design elicited two distinct steady-state responses: one at the base frequency (6 Hz) and another at the oddball frequency (1.2 Hz). Participants maintained fixation on a central cross, detecting occasional color changes (blue to red) lasting 400 ms, occurring six to eight times per trial at random intervals. This ensured engagement without explicitly attending to the stimuli. Four FPVS conditions were presented in

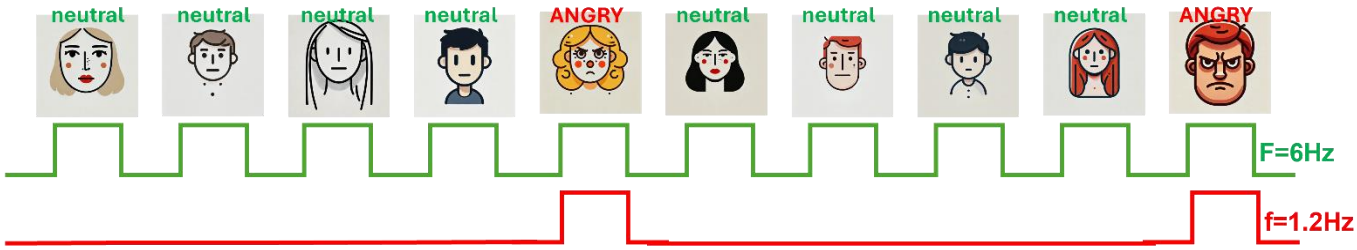

Figure 1. Schematic illustration of the experimental paradigm. Stimuli are presented at a rate of 6 Hz. In each 122 s stimulation sequence, base stimuli are selected from a large pool with oddball images presented at fixed intervals of one every fifth stimuli or 1.2 Hz. The example in this figure corresponds to condition D, angry faces. Note that only six faces are shown due to copyright and use agreement. The faces shown here is just for illustration, we used real photos in the experiments.

random order, each lasting approximately 122 seconds. Neutral faces served as base stimuli, while oddball stimuli consisted of happy, sad, fearful, and angry facial expressions.

2.4 EEG recording

EEG data were recorded using a 64-channel BioSemi ActiveTwo system (BioSemi, Amsterdam, Netherlands) with a sampling rate of 256 Hz. The reference was set to the average of the left and right mastoids.

2.5 EEG processing

EEG preprocessing was performed using MATLAB (MathWorks Inc.) and the EEGLab toolbox. Data segments included 2 seconds before and 3 seconds after each sequence, resulting in 127-second segments. A bandpass FIR filter (0.1-100 Hz) was applied. Channels exceeding five standard deviations from mean kurtosis values were identified and replaced via spherical interpolation. On average, fewer than 3% of channels were interpolated per participant. Data were re-referenced to the common average of all electrodes.

FPVS paradigms are relatively resistant to artifacts, allowing for meaningful neural responses without explicit correction for blinks or other artifacts (Rossion, 2014). Since the neural response of interest is confined to predefined frequencies, analysis is streamlined and highly reproducible across studies.

The preprocessed data segments were trimmed to an integer number of 1.2 Hz cycles, starting 2 seconds after sequence onset to avoid contamination from transient onset responses. A fast Fourier transform (FFT) was applied to extract normalized amplitude spectra across all channels and participants (Dzhelyova, et al., 2017). Prior research has demonstrated strong steady-state visual evoked potential (SSVEP) responses at oddball frequencies and their harmonics, with increased detection reliability when incorporating multiple harmonics (Retter, et al., 2021) (Stothart, et al., 2020).

Significant harmonics were identified by computing z-scores relative to the amplitude mean and standard deviation of the 20 neighboring FFT bins (10 bins on each side, excluding immediately adjacent and extreme values) (Dzhelyova, et al., 2017) (Naumann, et al., 2025). A z-score threshold of 1.64 ($p < 0.05$, one-tailed) was applied to determine statistical significance (Rossion, et al., 2015) (Quek & Rossion, 2017) (Lochy, et al., 2015). Group-level analyses examined the number of significant harmonics across all electrodes and within predefined regions of interest (ROIs): occipital (O: Oz, O1, O2), parieto-occipital (PO: POz, PO3, PO4), frontal (F: Fz, FCs, AFz), central-parietal (CP: CPz, CP1, CP3), and lateral occipito-temporal (left lOT: PO7, P7, P9; right rOT: PO8, P8, P10). The range of significant harmonics for each condition was determined as the last harmonic meeting statistical significance. Harmonics corresponding to the base frequency (e.g., 6 Hz, 12 Hz) were excluded (Stothart, et al., 2017).

To quantify facial expression discrimination at oddball frequencies, baseline-corrected amplitudes (BCA) were computed by subtracting the mean amplitude of 20 surrounding bins (excluding immediately adjacent and extreme values) and summing across the first 20

harmonics, excluding base frequency harmonics (6 Hz, 12 Hz). Significant harmonics were identified up to 14 harmonics in pooled data and up to 20 harmonics in individual participants. As including non-significant harmonics should have minimal influence on summed BCA values, responses were quantified across all channels and predefined ROIs.

Additionally, signal-to-noise ratio (SNR) was calculated for each frequency of interest as the amplitude value divided by the mean amplitude of the 20 neighboring bins (excluding adjacent and extreme values). SNR spectra were used for visualization, and grand averages of SNR and BCA were computed for each condition and electrode.

2.6 Statistical analysis

Group differences in summed BCA were assessed using two-sample t-tests ($p < 0.05$). Comparisons were conducted between anxiety and control groups for each emotional expression condition (angry, fear, sad, happy) across all ROIs (Lutz, et al., 2024). To examine frontal involvement, BCA ratios between frontal and posterior ROIs were calculated (e.g., F/O summed BCA, CP/rOT) and compared between groups.

3. Results

Analysis revealed strong responses at the oddball frequency (1.2 Hz) and its harmonics, as reflected in high signal-to-noise ratio (SNR) values across all conditions. Figure 2 illustrates SNR distributions for angry faces at CP and rOT ROIs. All four facial expressions (angry, fearful, happy, and sad) exhibited significant mean z-scores above the threshold ($z > 1.64$) at oddball frequencies and their harmonics across all electrodes and within specific ROIs.

Summed BCA analysis showed significant differences between groups for angry faces at the CP ROI ($p = 0.01$, $d = 0.73$), with the anxiety group displaying reduced responses ($M = 1.09$) compared to the healthy group ($M = 1.68$). Similar findings were observed for happy faces at CP ($p = 0.03$, $d = 0.6$), where the anxiety group ($M = 1.19$) exhibited lower responses than the healthy group ($M = 1.55$). For the frontal-to-posterior ratios, we found significant differences for

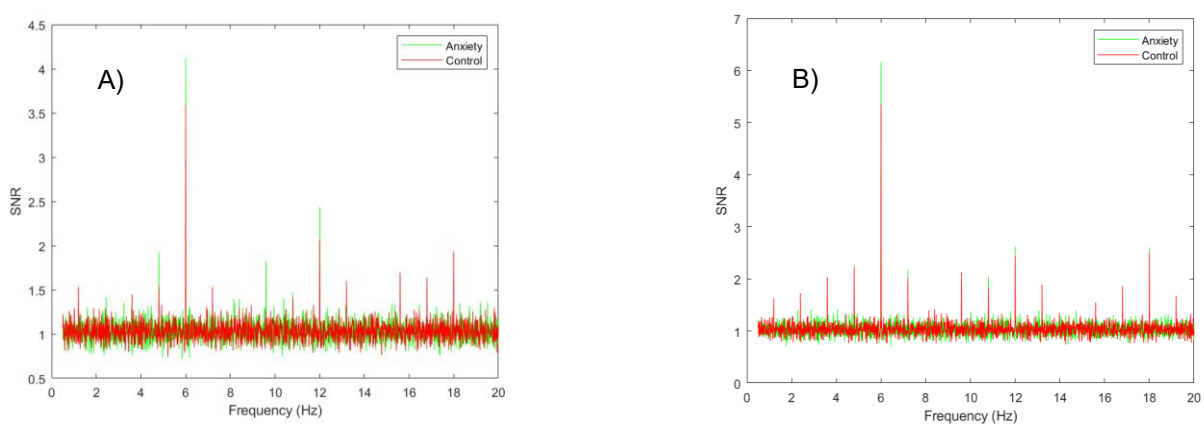

Figure 2: SNR plots of the FPVS condition with Angry faces as the oddball A) at Central-Parietal ROI and B) at right Occipito-Temporal ROI. The oddball responses are clearly seen in both ROIs. It can also be seen that the anxiety group has increased responses at the base frequency (6Hz) and harmonics, but decreased responses at the oddball frequency (1.2Hz) and harmonics. This could indicate hyper vigilance to all stimuli combined with threat-avoidance of the oddballs.

angry faces and happy faces, mostly in CP compared to O and OT ROIs. Table 1 presents the full set of significant findings

Table 1: Mean summed BCA responses for anxiety and healthy groups.

Condition	ROI	Summed BCA (mean ± sd) Anxiety	Healthy	p-value	Cohen's d
Angry	CP	1.09 ± 0.43	1.68 ± 0.94	0.01	0.73
Happy	CP	1.19 ± 0.34	1.55 ± 0.72	0.03	0.6
Angry	CP/O	0.29 ± 0.13	0.46 ± 0.23	0.007	0.8
Angry	CP/rOT	0.38 ± 0.16	0.5 ± 0.19	0.028	0.63
Angry	CP/lOT	0.45 ± 0.18	0.59 ± 0.18	0.015	0.71
Angry	CP/PO	0.43 ± 0.2	0.65 ± 0.25	0.004	0.85
Happy	F/rOT	0.57 ± 0.16	0.69 ± 0.16	0.02	0.67
Happy	CP/rOT	0.38 ± 0.09	0.52 ± 0.16	0.007	0.79
Happy	CP/lOT	0.47 ± 0.21	0.65 ± 0.38	0.04	0.57

4. Discussion

Our findings validate the utility of FPVS for assessing facial expression processing with ecologically valid and highly variable stimuli. This study demonstrated robust neural responses to emotional faces at both individual and group levels within short, two-minute recording sessions per condition, without requiring artifact removal in post-processing. Importantly, we observed significant group differences between the anxiety and healthy control groups, with moderate-to-large effect sizes. These results highlight the potential of FPVS to extract clinically relevant neural activity efficiently, making it a promising tool for clinical applications.

Anxiety disorders remain one of the most prevalent global mental health concerns, affecting approximately 301 million individuals in 2019 (World Health Organization, 2022). Despite their high prevalence, the neural mechanisms underlying anxiety remain incompletely understood (Nelson, et al., 2015) (Shadli, et al., 2021). Theoretical models of anxiety often emphasize attentional biases, proposing that anxious individuals exhibit heightened vigilance toward threat-related stimuli and difficulty disengaging from them (Bar-Haim, et al., 2007) (Mogg & Bradley, 2016). Such models predict that anxious individuals would show enhanced neural responses to threatening faces, reflecting hyperreactivity in early visual and higher-order processing regions (Frenkel & Bar-Haim, 2011).

However, our findings do not support this prediction. Instead, we observed attenuated responses to angry faces in the anxiety group, particularly in central-parietal (CP) regions, aligning with previous studies reporting reduced neural reactivity to threat-related stimuli in anxiety (Steinweg, et al., 2020) (Holmes, et al., 2008) (Frenkel & Bar-Haim, 2011). Given that FPVS measures the differential response between base and oddball stimuli, our results suggest that anxious individuals exhibit reduced sensitivity in distinguishing neutral from threatening faces. This may indicate a general hypervigilance toward all stimuli rather than a specific attentional bias toward threat (Steinweg, et al., 2020) (Walentowska & Wronka, 2012)

(Felmingham, et al., 2003). Supporting this interpretation, we found no significant differences between groups at early visual processing regions, such as the occipital (O) ROI. In fact, summed BCA values in occipital regions were nearly identical between anxious (M = 4.5) and nonanxious (M = 4.4) individuals, suggesting that early visual processing of facial expressions remained intact in both groups.

Another possible explanation is that anxious individuals engage in cognitive avoidance of threatening stimuli (Holmes, et al., 2008) (Steinweg, et al., 2020). Previous studies have suggested that avoidance of threat-related information is a core feature of anxiety, driven by inhibitory mechanisms that suppress later-stage processing (Steinweg, et al., 2020). This interpretation is consistent with our findings of significantly reduced CP-to-occipital connectivity in the anxiety group, suggesting impaired integration between early sensory and higher-order cortical areas. Such reduced engagement with threat-related stimuli may reflect dysfunctional regulation within cortico-limbic circuits, particularly disrupted interactions between the amygdala, prefrontal cortex, and related structures involved in emotion regulation and stress responses (Disner, et al., 2011).

In addition to differences in threat processing, we also found attenuated responses to happy faces in anxious individuals, with significantly lower summed BCA in CP regions compared to controls. This pattern was further reflected in reduced interactions between frontal and posterior regions, suggesting a diminished neural response to positive emotional stimuli in anxiety. One possible explanation is that anxious individuals exhibit an overall disengagement from emotional stimuli, a phenomenon that may be exacerbated by comorbid depression (Weinberg & Sandre, 2017) (Weinberg, 2023) (Dickey, et al., 2021) (Kujawa, et al., 2012) (Hill, et al., 2023). Given that several participants in our anxiety group reported comorbid depressive symptoms, future studies should further investigate whether these reductions in response to positive emotional expressions are driven by anxiety, depression, or their interaction.

While this study provides strong support for the feasibility of FPVS in assessing facial expression processing in clinical populations, several limitations should be acknowledged. First, although our sample size was relatively large for FPVS studies, it was limited in diversity, consisting primarily of college students, which may limit generalizability. However, given the high prevalence of psychopathology, including suicidality, among college students across multiple universities, this population remains relevant for investigating depression and anxiety (Barclay, et al., 2023). Nevertheless, future studies should aim to recruit more diverse populations, particularly individuals actively seeking mental health treatment. Additionally, anxiety diagnoses in this study were based on self-reported data and PROMIS Anxiety t-scores rather than structured clinical interviews. Incorporating clinician-administered assessments would enhance diagnostic accuracy and help account for comorbidities.

Furthermore, while our study broadly examined anxiety as a category, anxiety disorders are heterogeneous, encompassing multiple subtypes (e.g., social anxiety disorder, generalized anxiety disorder, panic disorder), each with potentially distinct neural signatures. Future work should explore whether different anxiety subtypes exhibit distinct patterns of facial expression processing using FPVS. Additionally, expanding this approach to other psychopathological populations, such as individuals with post-traumatic stress disorder (PTSD) or major depressive

disorder (MDD), may provide further insights into emotion processing abnormalities across clinical conditions.

The FPVS approach has previously been used to investigate facial and emotional sensitivity in children with autism spectrum disorder (Van der Donck, et al., 2019) (Vettori, et al., 2019). Our study extends this work by demonstrating that FPVS can differentiate anxious from healthy individuals based on their neural reactivity to facial expressions. Given its high signal-to-noise ratio, rapid acquisition time, and individual-level interpretability, FPVS represents a promising tool for both basic research and clinical screening of emotional processing deficits in psychiatric populations.

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