Personalized Emotional Contexts in Inhibitory Control Training for Trauma-Exposed Individuals

by

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A dissertation submitted to the Graduate Faculty of
Auburn University
In partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
August 8, 2026

Keywords: Inhibitory Control Training, Electroencephalogram (EEG), Event-Related Potentials (ERPs), Emotional Flanker Task, Trauma-Exposed

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Abstract

Roughly 50% of individuals experience at least one traumatic event in the course of their lives. However, not all individuals with a history of trauma develop post-traumatic stress disorder (PTSD). To understand the reasons for this discrepancy, we need to study the mechanisms that relate to the risks and maintenance of PTSD. Emerging evidence has shown that PTSD patients are characterized by a reduction in their ability to disengage from unwanted arousing stimuli, suggesting a deficit in their inhibitory control (IC). Previous research suggests that combining IC-demanding task trials with the processing of negative emotions can improve IC effectiveness in these contexts; however, results from a study by this author showed limited generalization of the IC training effect to new stimuli (i.e., near-transfer). Investigating the explanations of this null finding, the authors found that participants who showed greater emotional reactivity, as evidenced by increased late positive potential (LPP) amplitude, to the emotional context of the IC training (i.e., emotional generic faces), exhibited a greater near-transfer effect, as measured by a reduction in the IC-sensitive event-related potential (ERP) component called the N2. The current study aimed to enhance our previous research by introducing an additional condition in which the IC training occurs within a context specifically designed to heighten emotional reactivity in a trauma-exposed sample. We achieved this by tailoring the contextual stimuli to align with the participants' index trauma, in a sample of trauma-exposed adult females with elevated post-traumatic stress symptoms. Results showed that, similar to our previous findings, the IC-emotion association was established during the training blocks but did not generalize to novel stimuli. Moreover, the specific nature of the emotional stimuli did not seem to influence this training effect. We conclude that although the

IC training in an emotional context can improve IC outcomes for the trained emotion, the training effect does not transfer to new stimuli, regardless of the emotional salience of the context.

Artificial Intelligence (AI) Use Disclosure Statement

In the preparation of this dissertation, the following Artificial Intelligence (AI) tool was used: Grammarly. This tool was used primarily to edit the document and ensure consistency in language. The author acknowledges full responsibility for the intellectual content of this work and has ensured that all AI-assisted sections have been reviewed and revised for accuracy and appropriate academic style. All AI-generated content was reviewed and validated for relevance, appropriateness, and accuracy before incorporation into the final document to maintain scholarly integrity of this research.

Digital Accessibility Disclosure Statement

The author acknowledges full responsibility for the intellectual content of this work and has made a good faith effort to comply with digital accessibility requirements in publishing, wherein the nature of the content does not significantly change in order to do so. Furthermore, all content has been reviewed and revised to meet these requirements prior to final publication.

Acknowledgments

I would like to begin by expressing my sincere gratitude to everyone who helped make this milestone a reality. First, I want to thank my advisor, Dr. Richard Macatee, for supporting me throughout my graduate studies and for believing in my research ideas, especially regarding my dissertation project. I also want to thank my parents, Nadar Afshar and Katayoun Shams, who have always rooted for me. I appreciate my friends, especially TJ Preston and Mohammad Maydanchi, who were there for me during the personal challenges I faced in my second year. Finally, I want to thank my fiancé, Kabre Heck. Thank you for being my emotional rock and my best friend, for loving me for who I am, and for making me hopeful for the future. I could not reach this milestone without you. As our dog, Klaus, would say: it was ruff! But we did it.

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Introduction

Approximately 50% of people will experience at least one traumatic event in their lifetime (Kessler et al., 1995). However, only a fraction of those who have a history of trauma develop PTSD (Aupperle et al., 2012). Moreover, a review of the PTSD literature reveals that not all PTSD patients respond to extant treatments (Schottenbauer et al., 2008). This discrepancy could be explained by individual differences (e.g., behavioral, neurological, and psychological factors) among those exposed to trauma. At the neurobiological level, deficits in neural networks related to mechanisms like fear detection and emotion regulation have been linked to an increased vulnerability to developing PTSD symptoms after experiencing trauma (Prajapati et al., 2025). Therefore, further study of these mechanisms will enhance our understanding of the development and maintenance of PTSD.

Accumulating evidence suggests that deficits in inhibitory control (IC), one of the main cognitive processes involved in execution of goal-oriented and purposeful behavior (Carlson & Wang, 2007), may be one of the mechanisms related to fear processing and PTSD (Aupperle et al., 2012). Functional magnetic resonance imaging (fMRI) and neuropsychological studies employing IC tasks suggest that PTSD patients show reduced functional activity in brain areas associated with IC during IC-demanding tasks (Cisler et al., 2011; Falconer et al., 2008; Fitzgerald et al., 2018; LaGarde et al., 2010). For example, Falconer et al. (2008) found that increased PTSD severity was associated with diminished recruitment of executive IC networks such as the dorsolateral prefrontal cortex (dlPFC), right inferior frontal cortex (rIFC), and dorsal anterior cingulate cortex (dACC) during a Go/No go task. Thus, alterations in IC may be relevant in understanding the etiology of PTSD.

IC is an executive function defined by the capacity to disengage from irrelevant, salient stimuli and focus on goal-relevant stimuli (Egner, 2007; Miyake & Friedman, 2012). Several studies have utilized conflict-inducing tasks, such as the Flanker task (Eriksen & Eriksen, 1974), to study this mechanism (Braem et al., 2019; Clayson & Larson, 2011; Egner, 2007; Feldman & Freitas, 2019; Ligeza & Wyczesany, 2017). In conflict-inducing tasks, a conflict arises when a stimulus leads to two competing responses. For example, in the Flanker task, participants are required to identify the direction of the target stimulus (i.e., the center arrow) for congruent (<<<<< or >>>>) and incongruent (<<><< or >><>>) trials in a speeded response paradigm. In this task, a conflict is created by incongruent trials, where the target arrow is pointing in the opposite direction of the flanker arrows. When congruent trials are followed by incongruent trials, the resulting conflict causes a decrease in reaction time (RT), which helps the responder adapt. In studying IC, the slowing of RT for incongruent trials compared to congruent trials (i.e., congruency effect index [CEI]; incongruent RT – congruent RT) is used as a behavioral index of IC ability (decreased CEI interpreted as better IC). In the field of neurobiological analysis, previous work suggests that the ACC is responsible for detecting conflicts (Egner & Hirsch, 2005), and works in concert with other IC-related regions of the brain (e.g., dlPFC) to resolve the conflict (Banich, 2009; Egner & Hirsch, 2005). Likewise, results from event-related-potentials (ERPs) studies show that the N2 component, which is believed to be generated by the ACC (Luijten et al., 2014), is sensitive to conflict on IC tasks (e.g., Flanker; Clayson & Larson, 2011). Behavioral and neural indices of poor IC have been linked to PTSD symptom severity (Falconer et al., 2008), suggesting that impaired IC may be an important underlying mechanism of the disorder.

The importance of IC in the maintenance of PTSD symptoms can be explained by the attentional control theory (Eysenck et al., 2007), which suggests that anxiety may impair efficient attentional control toward emotional stimuli and increase attention to threat-related stimuli. Multiple studies have indicated that individuals with poorer attentional control tend to direct their attention toward emotional stimuli (Bremner et al., 2004; Morey et al., 2008, 2009; Pannu Hayes et al., 2009; Shin et al., 2005) and experience difficulties in shifting their attention away from such stimuli (Pineles et al., 2007, 2009). Additionally, results from fMRI studies reveal a correlation between difficulty disengaging from threat-related stimuli and the hyperactivity of brain regions involved in emotional processing, such as the amygdala (El Khoury-Malhame, Reynaud, et al., 2011). Furthermore, improvements in post-traumatic stress symptoms (PTSS), through exposure therapy, has been linked to enhanced adaptive disengagement from negative stimuli (El Khoury-Malhame, Lanteaume, et al., 2011). While overactivation of IC has also been associated with specific PTSD symptoms (e.g., avoidance; Bardeen et al., 2020; Bardeen & Daniel, 2017; Wald et al., 2013), deficits in IC are believed to play a significant role in the maintenance of PTSD symptoms.

Given the deficits in IC and their modulation by threat in trauma-exposed individuals, training IC activation during threat processing could have a therapeutic effect. Specifically, a successful IC training paradigm could benefit individuals by enhancing effective disengagement from threat-related distractors. For an IC training paradigm to be effective, IC must be adaptive and responsive to environmental changes, and it must be trainable in the context of other stimuli, such as threat cues. Although IC is typically conceptualized as a static ability, evidence suggests that it is dynamic and responsive to environmental demands (Clayson & Larson, 2011;

Spielberg et al., 2015). For example, Clayson and Larson (2011) showed that the amplitude of the conflict-sensitive ERP (i.e., the N2) is maximal when a congruent trial is followed by an IC-demanding incongruent trial, whereas the N2 amplitude decreases when an incongruent trial follows another incongruent trial. The authors suggest that consecutive incongruent trials prime IC activation, which leads to a decrease in N2 amplitude and faster RT, also known as conflict adaptation (Clayson & Larson, 2011). Moreover, in a study utilizing fMRI, Spielberg et al. (2015) demonstrated that as the demand for IC increases, the connectivity of key regions involved in IC also increases. These changes facilitate the global brain network to improve communication efficiency, optimize specialized processing, and enhance resilience to potential interruptions. Collectively, these studies suggest that IC is adaptive, and its activation is responsive to the temporal context (i.e., recency of IC demand).

In addition to IC adaptation to the temporal context, research has shown that IC activation can also be conditioned to specific stimuli categories, such as the spatial location (Crump & Milliken, 2009) and emotional (Cañadas et al., 2016; Afshar & Macatee, 2022) features of the stimuli. In these paradigms, IC conditioning to stimuli categories is achieved by presenting specific stimuli more frequently in contexts that are more IC demanding (Chiu & Egner, 2019). For example, in a non-clinical sample, Cañadas et al. (2016) superimposed emotional faces (e.g., angry or happy) on each trial of a flanker task. Four different faces were used for each emotion. To condition participants' IC activation to specific emotions, the researchers manipulated the association between IC demand trials and the type of emotional face shown. In one condition, three faces of one emotion (e.g., happy faces) were paired with 75% of incongruent trials (i.e., consistent faces), and one face of that emotion was paired with

25% of incongruent trials (i.e., inconsistent faces). The pairing proportions were reversed for the other emotion. Analyzing the RT congruency effect index (CEI; incongruent RT – congruent RT), the researchers found that participants had a smaller CEI to emotional expressions associated with a high proportion of incongruent trials than those associated with a low proportion of incongruent trials. Importantly, this effect was also found for emotional faces with the inconsistent pairing rate (Cañadas et al., 2016), suggesting generalization of IC associations to the emotion category.

In a similar study, Afshar and Macatee (2022) developed two conditions of an IC training paradigm by pairing emotional faces (e.g., fearful or happy) with a high proportion of incongruent (85% incongruent, 15% congruent) and low proportion of incongruent (15% incongruent, 85% congruent) flanker trials. The results indicate that the CEI, measured by the N2, was smaller for emotional expressions associated with a high proportion of incongruent trials compared to those associated with a low proportion of incongruent trials (Afshar & Macatee, 2022).

Both Cañadas et al. (2016) and Afshar and Macatee (2022) demonstrated that associations between IC demand and other categories, such as emotional faces, can be learned, similar to other forms of Pavlovian learning. However, unlike the findings of Cañadas et al. (2016), Afshar and Macatee (2022) did not observe a generalization effect of IC training to novel face stimuli in the same emotional category (i.e., emotional faces that were not associated with the same congruency bias). One possible explanation for this discrepancy could be the poor development of associations between IC trials and emotional stimuli due to insufficient attention allocated to the emotional features of the stimuli. This explanation is consistent with learning theories that emphasize the central role of attention in associative learning paradigms (Field & Moore, 2005; Kruschke, 2001). For example, in their study, Field and Moore (2005) explain the impact of attention on moderating evaluative conditioning, a process wherein neutral stimuli gain emotional significance through repeated pairing with a stimulus that already elicits an emotional response. The authors argue that in associative learning involving repeated pairing of conditioned stimuli (CS) and unconditioned stimuli (US), attention directed at a specific cue signifies the importance of that cue in predicting the outcome of the next trial (Field & Moore, 2005). Hence, attention to a CS increases the strength of the association between CS and US (Rescorla, 1972). Considering that motivation to pay attention to stimuli has also been associated with enhancing associative learning (Cañadas et al., 2013), it follows that, in an IC+emotion paradigm, participants who pay more attention to the emotional images are more likely to show a pronounced transfer effect.

To better understand the lack of generalization of the IC+emotion learning effect to novel stimuli in their study (Afshar & Macatee, 2022), the authors conducted an exploratory analysis of their findings, guided by the literature on the role of attention in IC learning (Field & Moore, 2005; Kruschke, 2001; Rescorla, 1972). Considering that Afshar and Macatee (2022) only recruited participants with a history of traumatic events (i.e., those who reported experiencing at least one traumatic event on the Life Events Checklist for DSM-5; Weathers et al., 2013), for their exploratory analysis, the authors hypothesized that the emotional stimuli (i.e., emotional faces) used in their study may not have been salient enough to elicit the level of attention necessary for the association between emotional images and IC demand to develop.

That is, the emotional faces used in training might have been too generic and low in self-relevance to effectively capture the attention of individuals with diverse traumatic experiences.

Afshar and Macatee tested this hypothesis by utilizing the late positive potential (LPP). LPP is a central-parietal ERP that is sensitive to attention allocation to emotional stimuli, and it is larger following the presentation of emotionally salient stimuli (e.g., pleasant and unpleasant pictures) than following neutral stimuli. (Hajcak et al., 2010). Moreover, the increased LPP for emotional images compared to neutral ones is often larger for stimuli that are rated as more intense or arousing (Cuthbert et al., 2000). In their exploratory analysis, Afshar and Macatee found that individuals who exhibited greater reactivity (i.e., increased LPP) to the emotional faces on which IC activation was trained (i.e., happy or fearful) showed a stronger generalization effect (i.e., reduced N2 on high vs. low IC-demanding trials).

Current Study

Considering that the moderating role of LPP on the near-transfer effect of IC+emotion training was a post-hoc exploratory finding of Afshar and Macatee's (2022) results, it is essential to further investigate the relationship between attention to the stimulus and its impact on generalization by experimentally manipulating stimulus salience. To achieve this goal, this study aimed to recruit participants who endorsed a specific category of trauma as their index trauma and tested the generalizability of the IC+emotion training using both generic stimuli (i.e., stimuli that are expected to evoke less attention) and stimuli tailored to participants' index trauma (i.e., stimuli that are expected to evoke higher levels of attention). Specifically, the present study recruited adult females who indicated their index trauma as interpersonal trauma (i.e., sexual assault, physical abuse, or domestic violence) and reported elevated PTSD symptoms on a brief PTSD screener. The present study employed a within-subject design to conduct an IC training in two contexts: general emotional stimuli (i.e., facial expressions) and stimuli tailored to participants' individual traumas (i.e., images depicting interpersonal relationships). The primary aim of the study was to determine whether the effectiveness of IC+emotion training is influenced by the emotional salience of the training stimuli in a sample of individuals exposed to trauma.

Hypotheses

We hypothesized the following: (1) Participants would show higher emotional reactivity, as indicated by larger LPP, to stimuli tailored to their trauma compared to generic facial expressions. (2) Participants would demonstrate improved learning of the IC-emotion association, as evidenced by quicker RTs and smaller N2 amplitude, when the IC training utilizes stimuli tailored to participants' trauma compared to generic faces. Lastly, (3) participants would show a greater transfer effect after receiving IC+emotion training in the context of tailored stimuli. This study aimed to provide insights into how individuals exposed to trauma respond to IC training, specifically concerning their attention to emotion-related contextual information. The goal was to enhance the understanding of the effectiveness of IC training and its implications for emotional regulation in the context of trauma.

Methods

Participants and Procedure

The sample included 43 adult females recruited from the community and Auburn University Psychology students through the SONA system. To be eligible for the study, participants had to be 18 years of age or older, fluent English speakers, screen positive for elevated PTSD symptoms on the Primary Care PTSD Screen for DSM-5 by endorsing at least three of the five questions (Prins et al., 2016), and report experiencing at least one interpersonal traumatic event, such as sexual assault, physical abuse, or domestic violence. We defined a 'traumatic event' according to Criterion A of the Diagnostic and Statistical Manual of Mental Disorders (5th ed.; DSM-5; American Psychiatric Association, 2013). Eligible participants were invited to complete the laboratory portion of the study.

The laboratory portion of the study was conducted over two visits. Participant demographics (Table 1), self-report surveys, and consent for participation was collected at the beginning of the first session only. During each session, participants completed two computerized tasks: the emotional image-viewing task and the emotional flanker training task. To test the study's hypotheses, we created two versions of these tasks. The first condition (i.e., Face Day) used close-up portraits of actors displaying discrete facial expressions (i.e., happy, fearful, neutral). In contrast, the tailored condition (i.e., Picture Day) employed contextualized scenes with a wider environmental frame, depicting individuals engaged in complex interpersonal dynamics (i.e., pleasant, unpleasant, neutral) relevant to the participants' traumatic experiences. Each participant completed both versions on different days. The two sessions were scheduled at least two days apart to minimize the chance of participants recalling the training task patterns.

Stimuli were presented using a Dell OptiPlex 7050 computer on a 21” LCD color monitor at a viewing distance of 100 cm, subtending a visual angle of 3.5°. All the tasks and instructions were presented using E-Prime 3.0 software. All participants were compensated for their time with either course credit or a monetary reward.

Laboratory Measures

Emotional Image-viewing Task

In this task, participants passively viewed various emotionally charged images, such as emotional faces or interpersonal dynamic-related pictures. At the start of each trial, a blue cross would appear, signaling the imminent appearance of the image. Participants were instructed to press the space bar when they would see the blue cross. Upon pressing the space bar, the blue cross would turn white and remain on the screen for one second, followed by the image for three seconds. Following the disappearance of the image, the screen would remain black for a randomly determined duration of 500–3000 ms (in steps of 500 ms) before the subsequent trial starts. The image-viewing task consisted of a total of six images depicting happy/pleasant, neutral, and fearful/unpleasant emotions, presented in four blocks, totaling 72 trials. Each block of the Emotional Image-viewing Task lasted around 2.5 minutes, with the total time for completion being approximately 10 minutes.

The emotional faces utilized in this task were chosen from the NimStim set of facial expressions (Tottenham et al., 2009). This set included 3 men and 3 women displaying happy, neutral, and fearful emotions. The images were modified to fit into an oval window, with the hair, neck, and surrounding areas darkened to remove any superfluous elements.

The stimuli used for the tailored image-viewing task contained pleasant scenarios (e.g., a couple displaying affection), neutral situations (e.g., two friends engaging in conversation), and unpleasant scenes (e.g., a man being violent towards a woman). These images were carefully chosen from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008). As some IAPS images may be disturbing, participants were notified about the potential inclusion of violent or sexually explicit content. They were also reminded of their autonomy to discontinue participation at any point during the study to ensure their well-being.

Subjective Arousal and Affective Valence Ratings

Following the completion of the primary image-viewing task, participants engaged in a behavioral rating procedure to assess their explicit emotional evaluations. Specifically, they re-viewed the emotionally charged stimuli (excluding neutral images) presented individually in a randomized order and provided subjective ratings based on two key dimensions: physiological arousal (emotional intensity) and affective valence (how they feel after viewing the stimuli).

For the emotional intensity metric, participants rated the perceived arousal of each image using a 1-to-9 Likert scale, with anchors ranging from 1 (“not at all intense”) to 9 (“extremely intense”). For the affective valence metric, participants assessed their own emotional state after viewing each image, indicating how happy/pleasant or fearful/unpleasant they felt in response. Responses were recorded on a 1-to-9 bipolar Likert scale, where 1 represented a completely happy/pleasant state and 9 signified a completely fearful/unpleasant state. All behavioral responses were entered manually by the participants using a standard laboratory response keyboard.

Emotional Flanker Training and Near-transfer Task

For the IC training task, we aimed to replicate the IC training task in Afshar and Macatee (2022). We utilized a modified version of the standard Flanker task (Eriksen & Eriksen, 1974). Specifically, during each trial of the traditional flanker task, participants were presented with five horizontally aligned arrowheads. For half of the trials, the arrows were congruent (<<<<< or >>>>>), while for the other half, the arrows were incongruent (<<><< or >><>>). Participants were instructed to quickly and accurately indicate the direction of the center arrow (left or right) by clicking the appropriate response key on a response box. In this modified version of the task, the arrows were superimposed on images, specifically emotional faces or tailored pictures. To ensure participants paid attention to the images before shifting their focus to the arrows, the target arrow (i.e., the center arrow) appeared 100 ms after the emotional image was presented. Additionally, participants were instructed to pay attention to the images, as they would be asked about them at the end of the experiment. All five arrows and the emotional images would remain on the screen for another 100ms. The arrows and the image would then disappear, followed by a blank screen remaining on the screen for 600ms, during which participants would respond. After the conclusion of the response window, there was a staggered ITI of 800-1200 ms before the next trial began.

In order to provide participants with brief pauses during the task, we split the total number of trials into seven equal blocks, with 144 trials in each block. The first six blocks served as training blocks, while the last block was intended to assess the generalization of emotional-cognitive demands to novel stimuli (near-transfer effect). For this purpose, the images in the training blocks matched those used in the Emotional Image-viewing task, while the seventh block (near-transfer block) featured six novel images. Throughout the training blocks, participants completed a total of 864 trials (50% incongruent, 50% congruent, 50% fearful/unpleasant, 50% happy/pleasant). However, unbeknownst to the participants, the images were unequally paired with incongruent versus congruent flankers during the training condition blocks. Specifically, during the training blocks, 85% of the incongruent trials were paired with fearful/unpleasant images, while 85% of congruent trials were paired with happy/pleasant images. In the final near-transfer block (i.e., the 7th block), 144 trials (50% incongruent, 50% congruent, 50% fearful/unpleasant, 50% happy/pleasant) involving novel images were presented. However, unlike the training blocks, the stimulus-congruency pairings in the near-transfer block were fully balanced (i.e., each image was paired with incongruent flankers 50% of the time). Participants were not informed of these alterations. Before starting the task, participants completed a 12-trial practice session to ensure a comprehensive understanding of the task. Each block of the Emotional Flanker Training and the near-transfer block lasted around 7 minutes, with the total time for completion of approximately 49 minutes.

Psychophysiology Data Acquisition

For the collection of EEG data, BrainVision products were utilized, including the BrainVision Recorder software, an actiCHamp amplifier (sampling frequency of 1000 Hz), and an actiCap 32-channel cap with active electrodes based on the 10–20 system. The midline electrode AFz was designated as the ground, and FCz was used as the online reference electrode. Electrooculogram (EOG) activity was recorded from electrodes positioned laterally to the outer canthus of each eye for horizontal EOG and from electrodes situated above and below the left eye for vertical EOG. Electrolyte gel was applied to reduce impedances to 10 kΩ or less. Following data acquisition, continuous EEG data were downsampled to 250 Hz to optimize computational efficiency during subsequent processing stages. The data were then re-referenced to the average of the mastoids. To eliminate low-frequency drift and high-frequency noise, a zero-phase-shift Butterworth infinite impulse response (IIR) filter was applied. In line with previous recommendations (Macatee et al., 2023), filter cutoffs were set to 0.01 Hz for the high-pass filter and 30 Hz for the low-pass filter. To correct eye movement artifacts, the algorithm developed by Gratton et al. (1983) was employed. Additionally, other artifacts such as muscle movements were eliminated in two stages following epoching of the data for each of the target ERPs (i.e., LPP and N2): (1) an automated statistical thresholding algorithm was used to reject whole-epoch and channels-within-epochs based on voltage range, deviation from the channel's mean voltage, and voltage variance (Nolan et al., 2010); (2) after automated rejection, any remaining artifacts were rejected through visual inspection.

Data Processing

N2

For the N2 analysis, data from the Emotional Flanker Training and the Near-transfer block were selected solely for correct response trials occurring within 300 ms before to 1600 ms after the presentation of the center arrow. The epochs were baseline-corrected using a -300 to -100 ms window, a time frame recommended by Clayson and Larson (2011) to account for the 100 ms delay between the appearance of the flanker arrows and the target arrow. After manual artifact rejection, clean epochs were separately averaged for congruent and incongruent trials presented with fear/unpleasant vs. happy/pleasant images. In line with

Clayson and Larson (2011), mean amplitude (+/- 16 ms) surrounding the local negative peak at FCz between 250-350 ms for each of the four averaged waveforms (fear/unpleasant + congruent, fear/unpleasant + incongruent, happy/pleasant + congruent, happy/pleasant + incongruent) was computed for each participant (Afshar & Macatee, 2022). An IC+emotion learning index was quantified using a difference score [i.e., (fear/unpleasant incongruent N2 – fear/unpleasant congruent N2) – (happy/pleasant incongruent N2 – happy/pleasant congruent N2)], such that more positive values would indicate greater learning of the IC + fear/unpleasant relative to IC + happy/pleasant association (Cañadas et al., 2016). The same difference score approach was used with RT in place of N2 amplitude.

Late Positive Potential (LPP)

For the LPP analysis, data from the Emotional Image Viewing task were analyzed using central-parietal pooling (Cz, Pz, CP1, and CP2; Parvaz et al., 2012; Versace et al., 2012; Webber et al., 2021) and were epoched from 400-3000 ms after the presentation of each emotional stimulus (Macatee et al., 2023). The epochs were then baseline-corrected using the -200 to 0 ms window. Clean segments from each emotional stimuli were averaged to create grand averages for happy/pleasant, fearful/unpleasant, and neutral faces/images. Difference scores for fearful/unpleasant (fearful/unpleasant – neutral) and happy/pleasant (happy/pleasant – neutral) images were then created to isolate these emotions (Hajcak et al., 2009).

Data Analytic Approach

Out of the 43 participants who attended their first visit, 12 did not show up for their second visit. This included 5 who missed Picture Day and 7 who missed Face Day. Additionally, five participants lack either LPP or N2 data due to excessive artifacts in their EEG recordings. Given that losing 17 data points is significant in our sample of 43, we chose to use statistical models, such as the linear mixed model (LMM), which uses maximum likelihood to estimate effects from partial information and is more resilient to missing data (Lo & Andrews, 2015). This approach is preferable to other models, such as repeated-measures ANOVA, which employs listwise deletion and may reduce statistical power in small samples with a high number of missing data. To ensure that our missing data was random and did not introduce systematic bias into our analysis, we conducted Little's Missing Completely at Random (MCAR) test. The results indicated that the pattern of missingness did not significantly deviate from a completely random distribution, X^2 (79) = 83.97, $p = .330$, thereby validating the use of maximum likelihood estimation without risking biased parameter estimates.

Our data analysis framework was structured as follows: The first hypothesis regarding ΔLPP amplitudes was evaluated using a 2 (Visit: Face vs. Picture) * 2 (Emotion: Positive vs. Negative) interaction. The second and third hypotheses concerning ΔN2 amplitudes and behavioral RTs were assessed via a three-way 2 (Visit) * 2 (Emotion) * 2 (Congruency: Congruent vs. Incongruent) interaction.

Post-hoc Power Analysis

To assess the statistical sensitivity of the observed three-way interaction (Visit * Emotion * Congruency) within the LMM framework for ΔN2 amplitudes, we conducted a post hoc Monte Carlo power simulation. Given our shift from using ANOVA to the LMM, we also transitioned to R 4.6.0, within the RStudio environment (Posit team, 2026) for our power analysis. Specifically, we employed the simr package (Green & MacLeod, 2016) in R, utilizing our empirical parameter estimates from our LMM results with a sample size of N = 43. This enabled us to create a simulation loop with 1,000 automated Monte Carlo iterations to evaluate the likelihood of detecting a significant fixed effect for the three-way interaction using a Wald Chi-Square (X^2) test as a baseline.

From these 1,000 iterations, the model demonstrated an achieved statistical power of 6.60% (95% Confidence Interval [6.12%, 7.11%]) at an alpha level of 0.05. This indicates a subtle observed effect size for the three-way interaction ($F(1, error) = 0.199$) within the current sample.

Results

Similar to other studies (Cañadas et al., 2016), the practice and the first block of training were considered learning trials; thus, their data were not included in the analysis.

Overall, participants demonstrated high accuracy on the emotional flanker task. Specifically, their average response accuracy during Picture Day was 92.43% in the training blocks and 88.29% in the near-transfer block. Similarly, for Face Day, the average response accuracy was also 92.43% in the training blocks and 91.83% in the near-transfer block.

Emotional Image-viewing Task

Late Positive Potential (LPP)

The main effect of Emotion was significant, $F(2, 165.45) = 19.38$, $p < .001$, suggesting that overall, emotionally positive ($M = 5.59$ µV, $SE = .49$, CI 95% [4.61, 6.57]) and negative ($M = 5.07$ µV, $SE = .49$, CI 95% [4.11, 6.05]) stimuli elicited higher LPP amplitudes than neutral (M =

2.72 μV, SE = .49, CI 95% [1.75, 3.70]) stimuli and that the task successfully captured expected emotional reactivity.

Our first hypothesis regarding the LPP was supported. Specifically, the Emotion * Visit interaction was significant, $F(2, 164.99) = 5.70$, $p = .004$. Overall, participants demonstrated higher emotional reactivity (i.e., more enhanced ΔLPP) toward stimuli tailored to their traumatic experiences compared to generic faces. We followed up this analysis with two separate 2 * 2 LMM analyses to determine whether the emotional valence of the stimuli differed between visits. Specifically, we conducted an analysis of Emotion (negative vs. neutral) * Visit (pictures vs. faces) to assess whether the ΔLPP for negative emotions varied between visits. Similarly, we performed an Emotion (positive vs. neutral) * Visit (pictures vs. faces) to evaluate whether the ΔLPP for positive emotions differed between visits.

Results revealed a marginally significant Emotion * Visit interaction for negative emotional stimuli $F(1, 97.161) = 3.833$, $p = .053$. The pairwise comparisons showed that, overall, participants showed a higher ΔLPP for unpleasant pictures (ΔLPP = 3.26 μV) compared to fearful faces (ΔLPP = 1.06 μV). In other words, the difference score between unpleasant pictures (M = 4.31 μV, SE = 0.60, 95% CI [3.13, 5.50]) and neutral pictures (M = 1.06 μV, SE = 0.60, 95% CI [-.127, 2.25]; Mdiff = 3.26 μV, SE = .67, $p < .001$) was larger than the difference score between fearful faces (M = 5.81 μV, SE = 0.59, 95% CI [4.65, 6.97]) and neutral faces (M = 4.37 μV, SE = 0.59, 95% CI [3.21, 5.53]; Mdiff = 1.44 μV, SE = .65, $p = .028$). Although the difference between the two ΔLPPs remained marginally significant.

Regarding positive emotional stimuli, the Emotion * Visit interaction was significant, $F(1, 96.127) = 9.186$, $p = .003$. Pairwise comparisons demonstrated that participants showed a larger

ΔLPP for pleasant pictures (ΔLPP = 4.47 μV) compared to happy faces (ΔLPP = 1.16 μV). In other words, the difference score between pleasant pictures (M = 5.56 μV, SE = 0.65, 95% CI [4.28, 6.83]) and neutral pictures (M = 1.08 μV, SE = 0.64, 95% CI [-0.18, 2.34]; Mdiff = 4.47 μV, SE = .78, p < .001) was larger than the difference score between happy faces (M = 5.52 μV, SE = 0.63, 95% CI [4.28, 6.77]) and neutral faces (M = 4.36 μV, SE = 0.62, 95% CI [3.13, 5.59]; Mdiff = 1.16 μV, SE = .76, p = .130). Surprisingly, the difference between happy faces and neutral faces was not significant (p = .130), suggesting that although participants showed higher emotional reactivity towards pleasant pictures compared to happy faces, results should be interpreted with caution, as this difference might be due to the nonsignificant ΔLPP for happy faces.

Subjective Arousal and Affective Valence Ratings

Although testing the differences in subjective measures between experimental conditions was not a primary hypothesis for the Emotional Image-viewing task, these behavioral evaluations serve as a useful manipulation check. Subjective ratings were analyzed using the identical LMM framework applied to the LPP findings.

For Arousal ratings, the overall Emotion * Visit interaction emerged as marginally significant, F(1, 106.75) = 3.78, p = .054. Similar to the follow-up LPP analysis, separate LMM analyses were conducted for negative (fearful faces and unpleasant pictures) and positive (happy faces and pleasant pictures) stimuli to test whether emotional arousal ratings for each emotion category systematically varied across testing visits.

For negative stimuli, the main effect of Visit was not statistically significant, F(1, 41.88) = 0.52, p = .477, indicating that participants did not evaluate the arousal intensity of generic fearful faces (M = 6.17, SE = 0.25, 95% CI [5.67, 6.66]) differently from unpleasant pictures (M =

6.42, SE = 0.25, 95% CI [5.93, 6.92]). Conversely, a significant main effect of Visit emerged for positive stimuli, $F(1, 37.22) = 4.80$, $p = .035$. Decomposing this effect revealed that participants rated generic happy faces (M = 6.68, SE = 0.23, 95% CI [6.22, 7.15]) as significantly more arousing than pleasant pictures (M = 5.99, SE = 0.23, 95% CI [5.52, 6.45]). These results suggest that the marginally significant Emotion * Visit interaction for arousal ratings is driven by the positive stimuli, specifically happy faces, rather than negative stimuli.

For Affective Valence ratings, the overall Emotion * Visit interaction was significant $F(1, 102.44) = 22.42$, $p < .001$. Looking at emotional categories separately, we found that the main effect of Visit was not significant for positive emotions, $F(1, 34.65) = 0.42$, $p = .522$, demonstrating that participants experienced happy faces (M = 4.29, SE = 0.29, 95% CI [3.71, 4.88]) and pleasant pictures (M = 4.07, SE = 0.29, 95% CI [3.48, 4.65]) as equivalently pleasant. However, a highly significant main effect of Visit was observed for negative stimuli, $F(1, 41.60) = 29.71$, $p < .001$. Pairwise tracking confirmed that unpleasant pictures (M = 6.02, SE = 0.29, 95% CI [5.44, 6.60]) were perceived as substantially more unpleasant compared to generic fearful facial expressions (M = 3.76, SE = 0.29, 95% CI [3.18, 4.34]). These results suggest that the significant Emotion * Visit interaction for affective valence ratings is driven by the negative stimuli, specifically unpleasant pictures, rather than positive stimuli.

Emotional Flanker Training and Near-transfer Task

Training Blocks

Analysis of the mean RT for the training blocks revealed a significant congruency effect, $F(1, 243.92) = 436.06$, $p < .001$. Overall, participants responded significantly faster to congruent trials (M = 448.61 ms, SE = 11.32, 95% CI [425.80, 471.42]) compared to incongruent trials (M = 513.17 ms, SE = 11.33, 95% CI [490.34, 536.00]). Moreover, the Visit * Congruency interaction was not significant, $F(1, 243.74) = 0.03$, $p = .873$, suggesting that the congruency effect was comparable on Face Day and Picture Day.

Further analysis revealed a similar congruency effect for the N2, $F(1, 217.85) = 6.16$, $p = .014$. As expected, incongruent trials elicited a more enhanced N2 amplitude (M = -3.67 µV, SE = 0.73, 95% CI [-5.14, -2.21]) compared to congruent trials (M = -2.96 µV, SE = 0.73, 95 % CI [-4.43, -1.50]). Similar to the RT findings, the Visit * Congruency interaction was not significant, $F(1, 217.85) = 0.35$, $p = .555$, indicating that the congruency effect was comparable for both Face Day and Picture Day.

Overall, our second hypothesis was not supported. Specifically, the Visit * Emotion * Congruency interaction was not significant for ΔRT, $F(1,243.74) = 1.09$, $p = .298$, or ΔN2 amplitude, $F(1,217.85) = 0.35$, $p = .553$. These results indicate that the magnitude of the congruency effect did not vary significantly as a function of Visit (face day vs. picture day) and emotional valence (positive vs. negative) during the training phase.

These null findings led us to investigate whether the learning effect occurred, regardless of the visit day. To investigate this further, we conducted a manipulation test of the interaction between Emotion * Congruency to determine whether the ΔRT and ΔN2 amplitude vary by emotion type (negative vs. positive). The results showed that the Emotion * Congruency interaction was significant for ΔN2, $F(1, 217.85) = 7.17$, $p = .008$, with more positive ΔN2 for negative emotional stimuli (fearful faces/unpleasant pictures; M = .06 µV, SE = .41, 95% CI [-.75, .86]) compared to positive emotional stimuli (happy faces/pleasant pictures; M = -1.48 µV, SE =

.40, 95% CI [-2.27, -.69]). However, the Emotion * Congruency interaction was not significant for ΔRT, $F(1, 243.74) = .021$, $p = .89$. The findings confirm the presence of an overall learning effect, which occurs only on the neurophysiological level and does not vary by stimulus type.

Near-transfer Block

As expected, the analysis of RT during the near-transfer block revealed a significant main effect of Congruency, $F(1, 244.82) = 247.06$, $p < .001$. Overall, participants responded significantly faster to congruent trials (M = 458.10 ms, SE = 12.54, 95% CI [432.85, 483.35]) than to incongruent trials (M = 520.56 ms, SE = 12.54, 95% CI [495.31, 545.81]). Surprisingly, the main effect of congruency was not statistically significant for the N2 amplitude, $F(1, 233.62) = 1.92$, $p = .167$.

Moreover, this congruency effect did not vary with the valence of the emotional background. This was confirmed by a non-significant Emotion * Congruency interaction for both ΔN2 amplitude, $F(1, 233.60) = 0.53$, $p = .468$, and ΔRT, $F(1, 244.82) = 0.17$, $p = .681$. Lastly, the three-way Visit * Emotion * Congruency interaction was not significant for ΔN2, $F(1, 233.62) = 0.20$, $p = .656$ or ΔRT, $F(1, 244.82) = 0.26$, $p = .612$, indicating that our Near-transfer hypothesis was not supported regarding behavioral or brain activity.

Discussion

The purpose of this study was to investigate whether the effectiveness of an emotional IC training paradigm is influenced by the emotional salience of the training stimuli in trauma-exposed individuals. We specifically proposed that (1) participants would display higher emotional reactivity, as indicated by a larger LPP, to stimuli that are tailored to their specific trauma compared to generic facial expressions, (2) participants would exhibit better learning of the IC-emotion association, evidenced by quicker RT and a more positive N2 amplitude, when the IC training occurs in the context of trauma-related pictures rather than generic emotional faces, and (3) participants would demonstrate a greater transfer effect (i.e., the generalization of IC+emotion learning to novel stimuli) after completing IC training in the context of tailored stimuli.

Overall, only the first hypothesis was supported. Specifically, participants exhibited higher emotional reactivity (i.e., ΔLPP) toward stimuli related to their traumatic experiences compared to generic emotional faces. However, further examination of the results introduced nuances to the interpretation of this hypothesis. Specifically, the face modality, which served as a manipulation check to measure emotional reactivity, was based on the assumption that fearful and happy faces elicit greater emotional reactivity (i.e., higher LPP) than neutral faces (Sun et al., 2017). However, in our sample, this assumption was validated only for fearful faces ($p = .028$), and not for happy faces ($p = .130$), raising the possibility that the apparent cross-visit difference in positive ΔLPP may be influenced by the initial lack of emotional reactivity to happy faces rather than a genuine increase in picture-driven emotional processing. Moreover, although participants showed higher emotional reactivity towards unpleasant pictures compared to fearful faces, the marginal difference between ΔLPPs of these two modalities ($p = .053$) suggests that their difference was not as large as anticipated.

The findings regarding the behavioral data were mixed. The LPP is thought to provide an objective indicator of emotional reactivity that complements other measures, such as self-reported emotional experiences (Hajcak & Foti, 2020). Therefore, we would expect the affective valence ratings to reflect the LPP results. Interestingly, in our sample, these two measures did not fully align. Both the subjective ratings and the LPP results indicated that participants exhibited higher emotional reactivity toward unpleasant pictures compared to fearful faces. However, this comparison achieved conventional significance only for the affective valence ratings and reached marginal significance for the LPP. Moreover, while ERP data suggested higher emotional reactivity for pleasant pictures versus happy faces, this difference was absent in the affective valence rating data.

Regarding arousal ratings, there was no difference between fearful faces and unpleasant pictures, whereas happy faces were rated significantly higher than pleasant pictures regarding arousal. Explaining the observed pattern of arousal and emotional reactivity ratings is beyond the scope of this paper; however, it may relate to the mechanisms behind how individuals assess intensity versus how they evaluate their feelings toward a stimulus (Mackes et al., 2018).

Regarding our second hypothesis, the interaction of Visit * Emotion * Congruency was not significant for both ΔRT and the ΔN2 component. These findings suggest that the N2 amplitude and response latency indices of IC did not vary across stimulus types (faces vs. personalized pictures) as a function of the IC training task.

Despite the absence of interaction between the training effect and stimuli type, our manipulation check revealed that the neurophysiological measure, rather than the behavioral measure, reflects the overall training effect. This was evidenced by a more positive ΔN2 for emotionally negative stimuli (i.e., fearful faces and unpleasant pictures) compared to emotionally positive stimuli (i.e., happy faces and pleasant pictures) during the training blocks.

This finding is consistent with previous studies that employed an IC+emotion training paradigm. For instance, Afshar and Macatee (2022) demonstrated a similar ΔN2 change for threat-related stimuli (i.e., fearful faces) compared to non-threatening stimuli (i.e., happy faces), particularly when threat-related stimuli were more frequently paired with incongruent trials.

A key difference between the current study and the research conducted by Afshar and Macatee (2022) is that, while their study limited emotional variations to facial expressions, the current investigation manipulated the delivery modality by introducing photographic picture contexts along with standard faces. Our aim was to determine whether higher emotional reactivity to stimuli affects the IC+emotion learning process. However, our findings show that despite the increased emotional reactivity towards tailored stimuli, the IC+emotion learning effect did not improve in our sample. Given this methodological difference, the replication of the IC+emotion learning effect found by Afshar and Macatee (2022) in our study is particularly intriguing. It suggests that the IC+emotion learning occurs, at a neurophysiological level, regardless of the degree of emotional reactivity to a stimulus.

Regarding RT, we did not observe an IC+emotion learning effect during the training block for ΔRT, which also replicates results from Afshar and Macatee (2022). As explained by Afshar and Macatee (2022), behavioral data may be less sensitive to changes in IC than neurophysiological markers. Additionally, the presence of emotional stimuli, such as fearful faces, during an IC task could consume attentional resources, leaving fewer available for adjusting responses (Pandey & Gupta, 2023), which may lead to slower response times (Reinhard et al., 2017). Given that we used faces and images with threat-related content, we may have introduced a wide variety of RTs within our sample, thereby impacting our results.

Contrary to our last hypothesis, the near-transfer effect did not materialize. This null finding is not surprising considering that the Visit * Emotion * Congruency interaction in the training blocks was also non-significant, suggesting that the type of stimuli does not impact IC+emotion learning. The lack of near-transfer effect is also aligned with previous findings, specifically Afshar and Macatee (2022), who did not find a near-transfer effect. Together, these findings suggest that the IC+emotion learning effect is stimulus-specific, meaning that it does not extend to new stimuli within the same category.

Two main reasons may explain the current results. One explanation for why we did not find a near-transfer effect could be due to the low statistical power of our study (6.6%). In our post-hoc power analysis, we ran a Monte Carlo simulation utilizing the empirical statistical parameters extracted from our near-transfer result. After 1,000 iterations, the simulation results closely matched our actual findings, suggesting that the underlying framework of our study was methodologically sound. However, design constraints, such as a small sample size or an insufficient number of training or near-transfer trials, made it difficult to observe a meaningful effect size.

Another reason could be the adaptive nature of IC. As Afshar and Macatee (2022) explain, IC shows a rapid adaptability to the requirements of the task (Afshar & Macatee, 2022; Grützmann et al., 2022). This adaptability could impact our near-transfer results in two main ways. Firstly, the significant variation in congruency pairing rates between training blocks (where 85% of incongruent trials were paired with negative images) and the near-transfer block (where 50% of incongruent trials were paired with negative images) in our design could trigger a rapid adjustment to IC, influencing the transfer of IC+emotion learning from the training blocks. Secondly, the near-transfer task introduces novel emotional stimuli, which can alter the attentional resources allocated to IC (Zhao et al., 2019), leading to a reduction in the transfer effect.

Limitations

There are three main limitations to the present study. First, although we aimed to maintain a homogenous clinical sample regarding post-traumatic stress symptoms (PTSS), we could not confirm whether any participants met the DSM-5 criteria for a PTSD diagnosis. This is important because individuals diagnosed with PTSD may process emotional faces—especially fearful ones—differently than trauma-exposed individuals without a PTSD diagnosis (Morey et al., 2009). This limitation may have introduced additional variability in our data. Future studies should include trauma-exposed participants with and without a PTSD diagnosis, as well as a symptom-free control group.

Second, the present study was underpowered. Our a priori power analysis indicated that a minimum sample size of N = 49 was required for our near-transfer hypothesis. However, recruitment constraints, particularly the narrow inclusion criteria that limited participants to females with interpersonal trauma, made it challenging to reach the desired sample size within the study’s timeframe. Despite our attempts to encourage participation through monetary compensation and course credit, a considerable number of participants (N = 12) did not complete their second visit. This reduced statistical power might have impacted our results and the effect sizes of our significant results. Future studies should address recruitment challenges and adjust their strategies and session lengths as necessary to ensure consistent attendance, which will provide adequate statistical power.

Lastly, this study only recruited adult female participants. Although our results resemble previous studies with similar paradigms (Afshar & Macatee, 2022), our findings might be impacted by the sex-dependent differences between men and women in IC functioning (Mansouri et al., 2016). Future studies should include both male and female participants to maximize the generalizability of the results.

Conclusion

In summary, this study sought to build on previous research that demonstrated an IC+emotions learning effect after sufficient training but failed to replicate these results with novel stimuli (Afshar & Macatee, 2022). We developed an IC+emotion training paradigm using personalized stimuli for trauma-exposed individuals. The goal was to explore whether these tailored stimuli would lead to a greater allocation of attentional resources and, consequently, a higher IC learning effect compared to IC learning in a generic context. We found that the IC-emotion association is established during the training blocks when negative emotional stimuli are disproportionately paired with IC-demanding trials of the Flanker task. However, this learning effect exhibited several distinct features that advance our understanding of cognitive control training frameworks. First, the IC+emotion learning effect was only captured at the neurophysiological level and was not reflected in the behavioral metrics. Second, the observed learning effect did not generalize to novel stimuli. Lastly, the specific nature of the emotional stimuli, whether generic or personally tailored to trauma, did not appear to moderate this training effect. While the first two patterns align with previous findings in the literature, the final observation represents an important contribution of the present study. We also discussed several limitations and explanations for why our analyses did not show the results we predicted, and we offered ways to improve our framework for future studies.

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Table 1. Participants' Demographics

Variable	n	%	M(SD)
Total Sample	43		
Demographics			
Age (years)	--	--	28.7
Sexual Orientation			
Heterosexual	33	76.70%	
LGBQ+ (Homosexual, Bisexual, Other)	10	23.30%	
Ethnicity			
White (non-Hispanic)	34	79.10%	
Black (non-Hispanic)	4	9.30%	
Hispanic	3	7.00%	
Other (Asian, American Indian)	2	4.60%	
Marital Status			
Single/Never Married	32	74.40%	
Married/Widowed	8	18.60%	
Divorced	3	7.00%	
Socioeconomic Status			
Education Level			
High school diploma	5	11.60%	
Some college	23	53.50%	
Bachelor's Degree	10	23.30%	
Post-Graduate Degree	5	11.60%	
Estimated Annual Income			
Less than $50,000	33	76.70%	
$50,000 - $100,000	8	18.60%	
Greater than $100,000	2	4.70%	

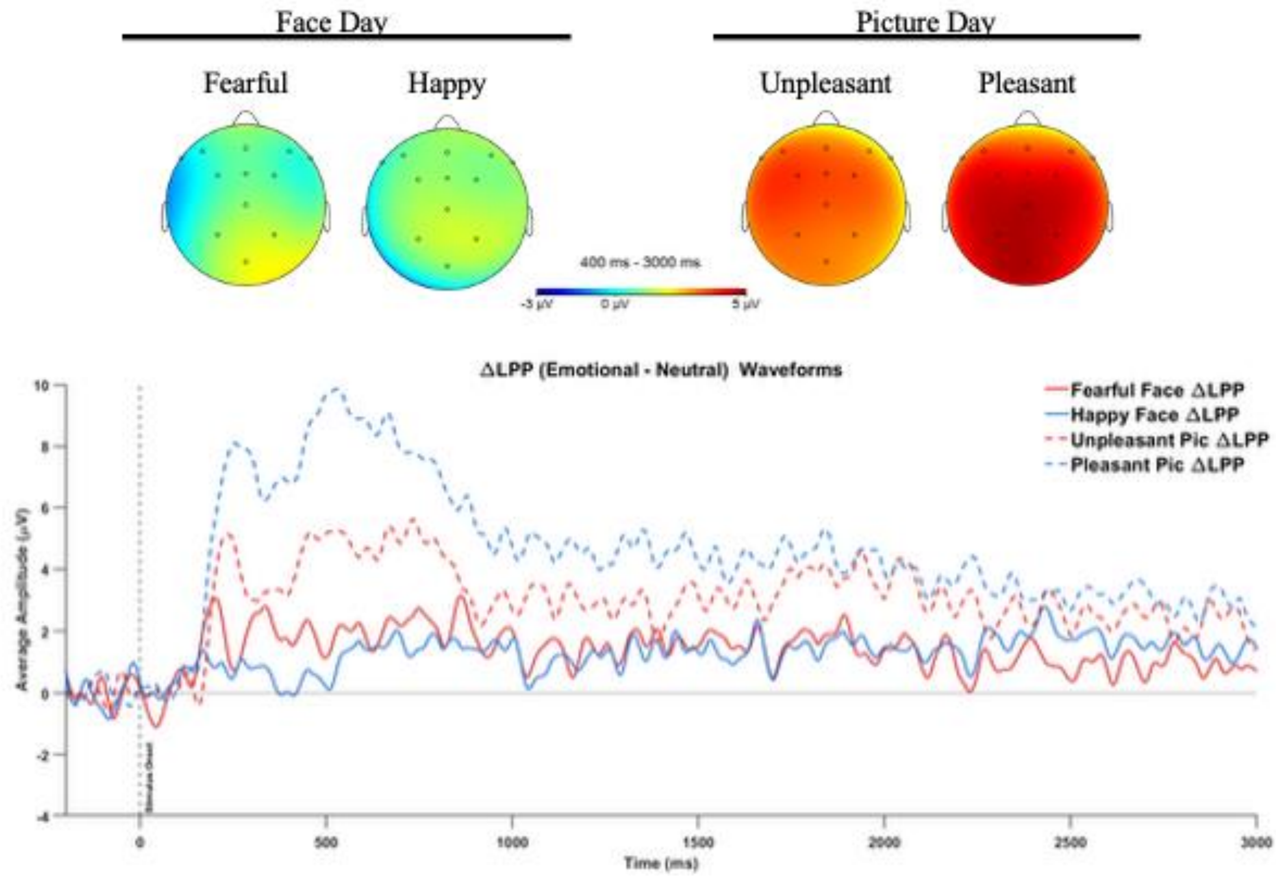

Figure 1. Topographic headmaps and waveforms for emotional facial expressions (fearful and happy) and personalized pictures (pleasant and unpleasant). Both topographic headmaps and waveforms show elevated ΔLPP for personalized stimuli. Difference waveforms are calculated by subtracting emotional images from neutral images within each category.

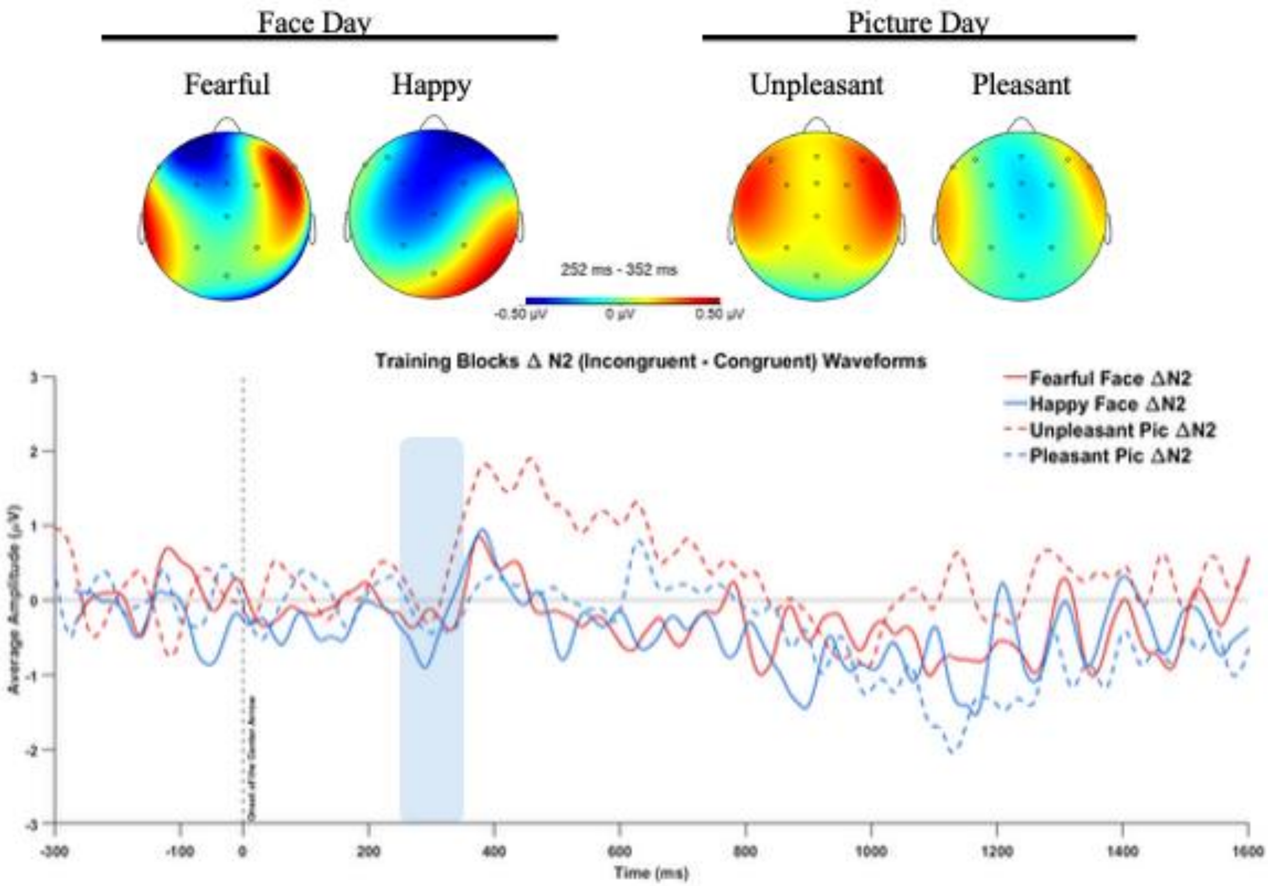

Figure 2. Topographic headmaps and waveforms, reflecting ΔN2 for emotional facial expressions (fearful and happy) and personalized pictures (pleasant and unpleasant) during the training blocks. Difference waveforms are calculated by subtracting congruent trials from incongruent trials.

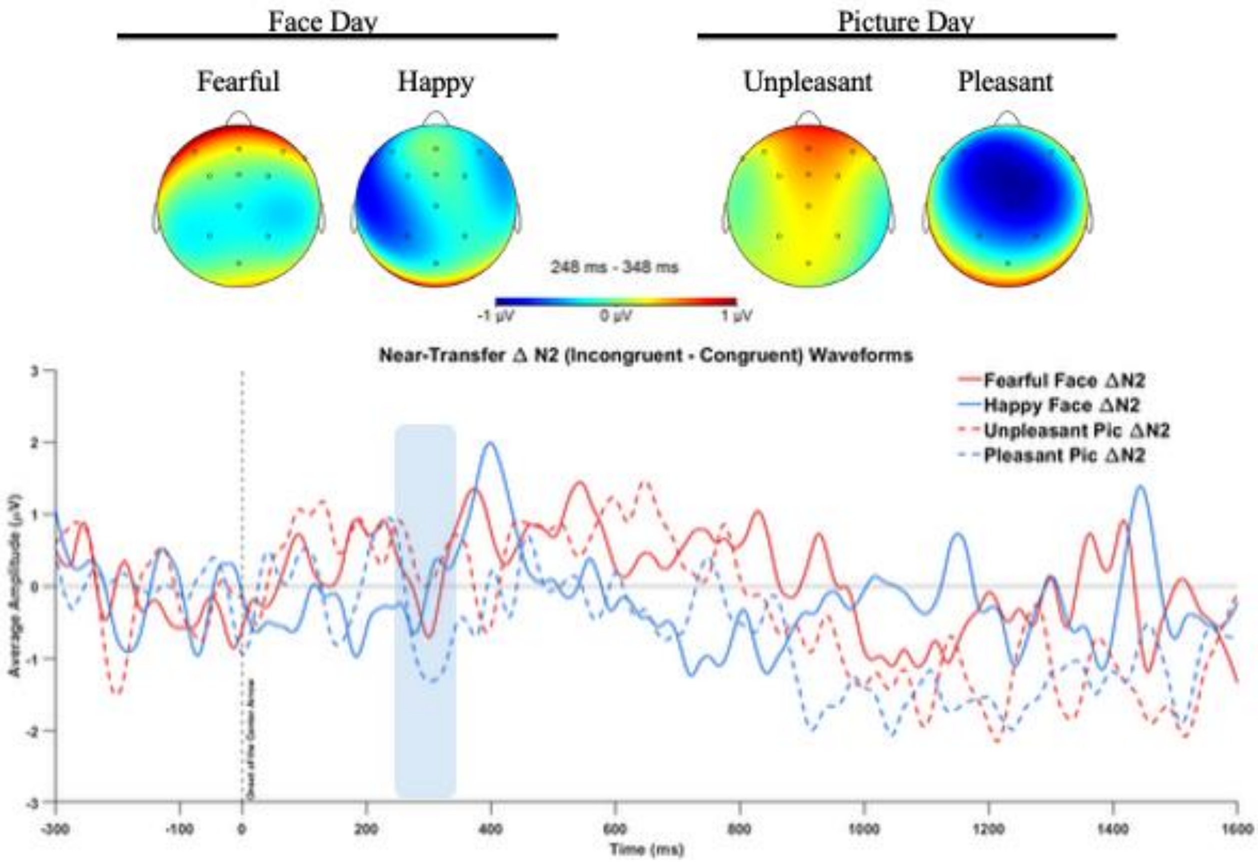

Figure 3. Topographic headmaps and waveforms, reflecting ΔN2 for emotional facial expressions (fearful and happy) and personalized pictures (pleasant and unpleasant) during the near-transfer block. Difference waveforms are calculated by subtracting congruent trials from incongruent trials.